MEDICAL RESEARCH COUNCIL

Special Report Series No. 298

Physiological Responses to Hot Environments

HER MAJESTY'S STATIONERY OFFICE

A seven-year programme of research, carried out under the direction of the Royal Naval Personnel Research Committee of the Medical Research Council, is described in this report. The investigations were conducted at the National Hospital for Nervous Diseases, Queen Square, London, and at the Royal Naval Tropical Research Unit, Singapore.

Detailed information was obtained on the physiological effects on groups of men of exposure to different hot climates. The relative contributions of air temperature, humidity and air speed to the severity of hot environments were evaluated; the effects of working at various rates of energy expenditure and the effects of wearing different amounts of clothing were investigated, and knowledge was acquired on the effects of radiant heat of long wavelength.

The work has thrown a great deal of light on the phenomenon of adaptation, or acclimatization, to hot environments. It has also provided useful information about the validity of the widely-used Effective Temperature Scale and of the Predicted Four-hour Sweat Rate—a new index of climatic severity that was developed in the course of the research.

This comprehensive report of a long and intensive series of experiments is likely to be an enduring source of fundamental data on climatic physiology. Moreover, it will be of value not only to the professional physiologist, but also to all people concerned with the practical problems of living and working in hot climates.

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No. 298

Physiological Responses to Hot Environments

An account of work done in Singapore, 1948-1953,
at the Royal Naval Tropical Research Unit
with an appendix on preliminary work done at
the National Hospital for Nervous Diseases, London

compiled by
R. K. MACPHERSON

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This report has been compiled under the direction of an editorial subcommittee specially appointed by the Climatic Physiology Committee. The members of the subcommittee were: O G. Edholm (*Chairman*), T. Bedford, F. P. Ellis and N. H. Mackworth.

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PREFACE

THE work described in this report had its origin in the concern expressed by the Board of Admiralty regarding the thermal conditions to which men were exposed during the Second World War when serving in His Majesty's ships in tropical waters. This led in 1944 to the appointment of a subcommittee (subsequently known as the Climatic Efficiency Subcommittee) of the Council's Royal Naval Personnel Research Committee to enquire into and advise on the problems in this field. It was recognised from the outset that investigations would eventually have to be made in a tropical climate, and in 1948 the Royal Naval Tropical Research Unit was established in Singapore under the joint auspices of the Admiralty and the Council. The background to this action is described in some detail in the first chapter of this report.

Before the establishment of the unit at Singapore, however, investigations were initiated in London at the National Hospital for Nervous Diseases. In these London experiments, the physiological effect on men wearing different types of clothing of exposure to high air temperatures was examined at different humidities and air speeds, both when the men were working and when they were resting. On the results of these experiments, for which the subjects had been artificially 'maximally acclimatized' by previous exposure to hot conditions in the laboratory, it was possible to base tentative recommendations concerning the conditions of warmth that were acceptable in ships at sea in tropical waters. The results also seemed to indicate that the Effective Temperature Scale, which had been accepted for use as the measure of the severity of the environment in H.M. ships, was misleading in certain respects. This led Dr. B. McArdle to devise a new index, the Predicted Four-hour Sweat Rate (P4SR), for the assessment of hot environments.

With the establishment of the unit at Singapore similar studies were made. These largely confirmed the previous findings in London and though they did not entirely support the criticisms of the Effective Temperature Scale they did demonstrate that the Predicted Four-hour Sweat Rate was an accurate and convenient measure of the severity of indoor hot environments. The work at Singapore was, however, extended to compare the relative tolerance to heat of men who had been artificially 'maximally acclimatized' in the laboratory and those who had been 'naturally acclimatized' by residence in a tropical climate. Investigations were also made of the stress imposed by radiant heat of long wavelength and by different rates of energy expenditure. Studies made to determine the upper limits of warmth to be permitted in ships were extended to determine the upper limits that could be physically tolerated and the position of the 'comfort zone'. In addition a number of physiological problems associated with these main lines of research were also examined.

Now that the results of all the investigations in London and in Singapore have been brought together, it is clear that considerable additions to knowledge have been achieved. Much information has been obtained on the relative effects of various levels of air temperature, humidity, air speed, and radiant heat, and about the limits of heat that people can tolerate. Answers have been provided to some of the practical problems of the Navy; and the critical examination of a widely used scale of environmental heat stress and the production and testing of a new index have improved and added to the techniques available for evaluating the severity of different climatic environments. As well as achieving these practical ends, the studies have extended knowledge of the physiological mechanisms involved in the process of adaptation to hot environments and have indicated the direction for future research.

* * *

The investigations in London and Singapore were made possible only by close collaboration between the Admiralty and the Council, assistance from the Colonial Office and the War Office, and the cooperative efforts of a great number of people. Considerable difficulties had to be overcome, and among the many people who contributed to their solution only a few can be mentioned here.

The late Sir Edward Mellanby, as chairman of the Royal Naval Personnel Research Committee, and Professor Sir Lindor Brown, as secretary and subsequently chairman of this committee, played an important part in the direction of the research programme.

Surgeon Captain F. P. Ellis, first as Naval Medical Secretary to the Royal Naval Personnel Research Committee and then as secretary to the subcommittee concerned with the investigations, was a key figure without whose initiative the whole project might have foundered. Later, as Director of the Unit throughout its five years of existence, he closely supervised the whole programme and took an active part in the experimental work.

Dr. T. Bedford (late of the Council's staff) was also closely associated with the whole programme of investigations. From the time of the appointment of the Subcommittee in 1944 until the completion of this report he advised on technical matters and gave his constant support to the work.

The completion of the London research programme in a remarkably short time was in great part due to the enthusiastic support of the late Surgeon Vice-Admiral Sir Sheldon Dudley, wartime Medical Director General of the Navy, of Sir Charles Goodeve, then Assistant Controller (Research and Development), Admiralty, of Dr. (then Surgeon Captain) Macdonald Critchley, wartime chairman of the Climatic Efficiency Subcommittee of the Royal Naval Personnel Research Committee, and of Dr. E. A. Carmichael, who directed the research at the National Hospital for Nervous Diseases.

In the negotiations which led to the establishment of the research unit in Singapore the help given by Sir George Allen, first Vice-Chancellor of the University of Malaya, and by Professor R. G. Scott MacGregor, Head of the Physiology Department of the King Edward VII Medical College, was invaluable. Admiral Sir Denis Boyd, Admiral Sir Patrick Brind, and Admiral the Honourable Sir Guy Russell, who were the Commanders-in-Chief, Far East Station between 1948 and 1953, all took a close personal interest in the Singapore work; Vice-Admiral Clifford Caslon, Rear-Admiral H. W. Faulkner, and Rear-Admiral A. F. Pugsley, who were the Flag Officers, Malayan Area and Admiral Superintendents, H.M. Dockyard, Singapore, were administratively responsible in turn for the indispensable support provided by H.M. Navy; and Mr. W. Wight and Rear-Admiral N. E. H. Clarke, who at that time were the Superintending Civil Engineer and Deputy Chief Engineer, H.M. Dockyard, respectively, built the laboratory, installed the plant and generating station, and provided excellent maintenance facilities throughout the existence of the Unit.

The results that were achieved in Singapore also owed much to a number of scientists from outside the Unit who gave technical advice and assistance. These included Dr. Ezer Griffiths of the National Physical Laboratory and

Dr. J. O. Irwin of the Council's Statistical Research Unit. Dr. Griffiths advised on the measurement of the environment and, as chairman of the Radiant Heat Panel of the Royal Naval Personnel Research Committee, with the assistance of Mr. F. E. E. Smith ensured the development and timely installation of the equipment necessary for the experiments on the effects of radiant heat. Dr. Irwin, whose demonstration that statistical procedures developed for use in other fields could be applied to these investigations was of considerable importance, designed the first series of experiments in Singapore, analysed the results and advised on the design and the analysis of the results of subsequent experiments.

* * *

The present publication is based on a long series of reports submitted to the Royal Naval Personnel Research Committee by the workers in London and Singapore. At the instance of the Council's Climatic Physiology Committee, and with the assistance of an editorial subcommittee, it has been compiled by Dr. R. K. Macpherson, who has also reviewed the implications of the major findings. The Council are aware of the complexity of the compiler's task and are grateful to Dr. Macpherson for undertaking this arduous work.

MEDICAL RESEARCH COUNCIL,
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London, S.W.1.

16th June, 1960

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CHAPTER 1. THE ESTABLISHMENT OF THE ROYAL NAVAL TROPICAL RESEARCH UNIT

The Wartime Background

THE work on climatic physiology about to be described had its beginning on 17th November, 1942, when the Royal Naval Personnel Research Committee of the Medical Research Council, with the late Sir Edward Mellanby as Chairman, held its first meeting. The Committee had been constituted in response to a request from the Board of Admiralty that the Council should establish a committee to advise on matters concerning personnel problems in the Royal Navy. At this first meeting it adopted as its terms of reference 'to advise the Medical Research Council on such investigations as the Council may be asked to undertake in psychological and physiological aspects of matters affecting the safety and efficiency of Royal Naval personnel in warfare'.

The immediate need was for information concerning the nature and scope of such problems in the Navy. At its second meeting, therefore, the Committee decided that Surgeon Captain Macdonald Critchley, R.N.V.R., should make observations on the environmental conditions in ships in the Russian convoys and that Surgeon Commander R. A. Graff, R.N., Dr. B. S. Platt, and Dr. G. L. (later Sir Lindor) Brown should visit Coastal Forces for a preliminary survey of conditions there.

The result of Critchley's observations ('Memorandum on medical conditions observed during passage on Northern Convoy, in Russia, and in Iceland'), presented to the Committee in April, 1943, proved so valuable that he was immediately requested to undertake the further task of surveying, with Surgeon Lieutenant-Commander H. E. Holling, R.N.V.R., environmental conditions in the Mediterranean, Levant and Eastern Fleets. In April, 1944, these two observers presented to the Medical Director General of the Navy a memorandum entitled 'Living and working conditions among Royal Naval personnel in the tropics'. This memorandum revealed such a serious state of affairs that a special meeting of representatives of Admiralty Departments directly concerned was called to consider it. This meeting discussed the matter from various aspects but decided that from its point of view the problem of environmental temperature was most urgent.

Critchley's report provided ample evidence that, in ships at sea, conditions of temperature and humidity occurred, both in working spaces and on the mess decks, that would, in ordinary language, be described as intolerable. The viewpoint of the meeting was, however, somewhat different. It found that—'The present conditions in H.M. ships in the tropics are far inferior to the comfort level and undoubtedly result in loss of efficiency. . . . Habitability as a problem in the Navy is concerned not with comfort but with loss of efficiency. If we followed our standard organisational practice, the Naval Staff would propose what is the lowest percentage of maximum efficiency that would be acceptable. Medical officers and scientists would convert this into a measurable scale describing the physical conditions and the constructors and engineers would examine what additional equipment or sacrifice of water-tightness, etc., would be necessary to meet the efficiency requirement. The latter might well ask for a revision of the requirement in the light of their examination.'

The steps in this approach are clear. The next phase would be the determination of the level of environmental stress at which the acceptable reduction in efficiency occurred. It was realised, however, that environmental stress is dependent on several factors—air temperature, humidity, radiant heat, air speed, rate of work and amount of clothing worn—so that before any level of environmental stress could be prescribed there was the prior problem of selecting a scale by which it could be defined. The choice of the meeting fell on the Effective Temperature Scale, a widely used scale of warmth which had been devised in the Research Laboratory of the American Society of Heating and Ventilating Engineers and which took into account the effects of air temperature, humidity and air speed.

The problem then became to relate the Effective Temperature Scale to loss of efficiency, and further, since this scale took account only partly of the amount of clothing worn and took no account of the rate of working or of the level of radiant heat, additional research work was required to integrate these factors into the scale. Furthermore since some assessment would have to be made of the effect of acclimatization, it would be necessary to carry out work in the tropics and correlate it with any work in this country.

Having reached these conclusions, the meeting decided that a request should be made to the Royal Naval Personnel Research Committee to set up a subcommittee to advise on these matters and direct the necessary associated research. This request was readily acceded to and on 15th May, 1944, the Ventilation Subcommittee of the Royal Naval Personnel Research Committee held its first meeting. Critchley was chairman and Surgeon Lieutenant-Commander F. P. Ellis, R.N., then Naval Medical Secretary of the R.N.P.R.C., was appointed secretary. The Subcommittee was shortly afterwards renamed the Habitability Subcommittee and in 1948 it became the Climatic Efficiency Subcommittee, under which name it still functions.

At the early meetings of the Subcommittee a policy was formulated which determined the direction of the subsequent research work for more than ten years. At the first meeting it was decided that Dr. T. Bedford should draw up a 'lucid and precise definition of Effective Temperature' and 'prepare a memorandum on the methods which might be employed to relate the effects of radiant heat to the Effective Temperature Scale'. On the subject of future research the Subcommittee agreed that there was a very urgent need for further knowledge on the effects of life in hot climates, that experimental work in hot rooms in temperate climates, although valuable, would not provide a satisfactory answer to this problem and that the establishment of a research organization in a tropical climate was essential—a view first expressed by Mr. M. G. Bennett (later chairman of the Climatic Efficiency Subcommittee).

At the second meeting, held only eleven days after the first, Bedford presented two memoranda entitled 'Effective temperature and its measurement' and 'Effective temperature adjusted to allow for radiation'. On the basis of these two memoranda and the discussion which followed it was decided that this 'Corrected' Effective Temperature Scale should be adopted as the official scale of environmental warmth, that sets of instruments necessary for the determination of 'corrected' effective temperature should be issued to ships, and that a precise book of reference should be prepared for instruction in their use. This last was the origin of the now widely used 'Environmental Warmth and its Measurement' (Bedford, 1946).

At this meeting the Subcommittee also considered the problem of defining the upper limits of environmental warmth which could be accepted without risk of serious loss of efficiency. It phrased its recommendation as follows.

'. . . a corrected effective temperature of 80°F is the desirable upper limit for the compartments of ships which is compatible with reasonable efficiency, but the Committee are prepared to accept a corrected effective temperature of 86°F as the upper tolerable limit. When the outside air temperature exceeds 100°F it is appreciated that a C.E.T. of 86°F may prove difficult to attain, in which case some [further] loss of efficiency may have to be tolerated.'

This resolution has been quoted verbatim because it is important to note the meaning to be attached to the words 'desirable upper limit' and 'upper tolerable limit'. The concept of 'desirable upper limit' can readily be appreciated, and the meaning attached to it by a naval constructor and by a physiologist would be much the same. The phrase 'upper tolerable limit', however, appears from the context to be used here not in a physiological but rather in an engineering sense as indicating a permissible deviation from the desired value.

By its third meeting the Subcommittee was in a position to formulate its general proposals for future work (Medical Research Council, 1944). They included:

1. The determination of the physiological cost (energy requirements in terms of oxygen consumption) of selected representative tasks in ships or at training establishments.
2. The assessment of the physiological effects of the performance of tasks of known energy requirements in a controlled hot environment in England.
3. The adaptation of standard tasks of skilled naval ratings, or the modification of existing techniques, as tests of performance which could be applied in a controlled hot environment.
4. The compilation of more complete and accurate information on the conditions now existing in H.M. ships by a medical officer who should visit the Eastern Fleet in company with an engineer or constructor who could consider the application of 'first aid' remedies.
5. The establishment of a unit for physiological and psychological research in India, at a place frequently visited by ships of the Eastern Fleet containing naval barracks and provided with laboratory facilities.

In these proposals the beginnings are to be seen of the greater part of the research conducted under the auspices of the Subcommittee. In the second proposal we have the initiation of the work at the National Hospital for Nervous Diseases, Queen Square, London; the third led to work done in the Department of Applied Psychology in the University of Cambridge, the fourth to a mission to examine conditions in the Eastern and British Pacific Fleets by Ellis and Holling together with Constructor Lieutenant-Commander E. A. Brokensha, R.C.N.C., and the fifth to the establishment of the Royal Naval Tropical Research Unit in Singapore.

The Neurological Research Unit of the Medical Research Council at the National Hospital was particularly fitted to undertake research on the effects of hot environments. This unit, under the guidance of the Director, Dr. E. A. Carmichael, had been engaged in research on personnel problems in the Services since the early days of the war and, in 1942, a team of workers under the direction of Carmichael had begun work (on behalf of the Military Personnel Research Committee) on the effects of hot environments on man. At first, a small 'hot-room' at the London School of Hygiene and Tropical Medicine had been used, but later another had been erected at the National Hospital. In the course of this work much valuable information had been acquired on the effects of heat and on practical methods for their mitigation. Moreover in 1943 two members of the Unit, Dr. W. S. S. Ladell and Dr. J. C. Waterlow, had studied the physiology of heat casualties in the field in Iraq. In 1944, then, there was already in existence an organization whose members had gained experience in hot-climate physiology, and which was prepared to extend its activities to deal with the special problems of the Navy.

Arrangements were made for the Navy to build two further climatic chambers at the National Hospital. These were equipped from the joint resources of the Admiralty and the Medical Research Council. A programme of research was drawn up and embarked upon. It had among its aims:

1. To determine the critical body temperature, in relation to duration of exposure, above which the performance of routine tasks is likely to be adversely effected.
2. To determine the body temperature reached with different rates of work over given periods of time and at different effective temperatures.
3. To define limiting effective temperatures at which routine tasks may be satisfactorily carried out and the permissible duration of such tasks.

The relation of these aims to the second major objective of the Subcommittee is clear. Research, however, is no respecter of plans, and the work that was done both at the National Hospital and, later, at Singapore broadened in scope as new problems and areas of interest came to light. For example, the research concerned with defining limiting effective temperatures for the efficient performance of specific tasks led to the investigation of the upper limits of heat that could be physically tolerated. Nevertheless the basic objective was steadily adhered to throughout.

With regard to the third main objective, the devising of tests of performance, the Subcommittee was again able to take advantage of an existing organisation, the Applied Psychology Research Unit of the Medical Research Council which had been established at Cambridge early in 1944. Its Director, the late Dr. K. J. W. Craik, had had experience in personnel problems in the Army and Royal Air Force and the Unit, which included Dr. N. H. Mackworth, had been concerned with the measurement of performance and the general problem of fatigue. Mackworth had already designed two pieces of apparatus for measuring the performance of radar operators which were thought suitable for use in testing subjects in a hot-room. The installation by the Admiralty of climatic chambers at Cambridge enabled Mackworth to begin work on the effects of high environmental temperatures without delay. With the untimely death of Craik in 1945, Professor F. S. (later Sir Frederic) Bartlett became Honorary Director of the Unit and the work continued under his direction. When the Royal Naval Tropical Research Unit at Singapore was established, Mr. R. D. Pepler was able to repeat Mackworth's work and to show that the results obtained in a hot-room at Cambridge could be applied to men living in the tropics.

By November, 1944, considerable progress had been made along all the lines laid down by the Subcommittee (p. 3). Observers appeared to be agreed that the heaviest physical work on board ship (apart from infrequent operations in the engine and boiler rooms) was that performed by guns' crews; furthermore, it had become apparent that environmental conditions in magazine and shell rooms, especially in the 'closed down' condition, became extremely difficult, and that a determining factor in the rate of fire of major armaments was the capacity for physical work of the men in the magazines. Accordingly Dr. J. A. B. Gray had been measuring the energy expenditure of guns' crews in magazines and cordite handling rooms, and the National Hospital workers, who were able to report good progress in the assessment of the physiological effects of standardized tasks in controlled hot environments, had adopted a conventionalized representation of the activities of these crews during battle as the standard work routine performed by their subjects. (This routine developed into the 'Queen Square Routine' (p.15) and as such was used at Singapore). To simulate action conditions further, it was decided that the clothing worn for experimental purposes should conform with that stipulated by Admiralty regulations. This led to the adoption of cotton drill shorts and overalls worn over shorts (to represent 'anti-flash' clothing) as the standard dress in the experiments at the National Hospital and later in Singapore.

In other fields, Mackworth was able to report good progress with the work on the tests of performance at Cambridge, and the compilation of more complete and accurate information on conditions in ships was proceeding, the 'Habitability Mission' of Ellis, Holling and Brokensha to the Eastern Fleet having already collected much useful information. Progress had also been made towards the establishment of a research unit in the tropics. Critchley, accompanied by a new member of the Subcommittee, Professor H. C. Bazett of the University of Pennsylvania, had gone to India and was able to report in October that a site for the proposed laboratory had been found in the Grant Medical College, Bombay. In November Critchley and Bazett presented a formal report setting out proposals for the organization of the unit and the nature of the research to be conducted. In this report the important point was made that 'Emphasis must be placed on the determination on a number of men of the conditions which lead to physical or mental inefficiency and its quantitative assessment, rather than any detailed analysis of the causes of such inefficiency'.

By April, 1945, however, it had become clear that, for various reasons, living and working conditions were likely to prove unsatisfactory in Bombay and that an adequate supply of subjects would not be available there. Nevertheless the Subcommittee was insistent that the main results obtained at the National Hospital should be confirmed in the tropics before they were used as the basis of far-reaching recommendations and that, if Bombay was unsuitable, then a tropical site for a research unit must be sought elsewhere.

In July it was decided, on the advice of the Supreme Allied Commander South-East Asia, Admiral Lord Mountbatten, that the establishment of the unit should be delayed until the recapture of Singapore when the unit should be established there. In September, when Singapore had been recaptured, negotiations for the setting up of a unit in the King Edward VII College of Medicine were undertaken by Surgeon Captain S. G. Rainsford, R.N., and in December his proposals were accepted by the Subcommittee and a programme of work decided upon.

It was at this time that the two reports of the Habitability Mission to the Eastern Fleet were circulated. The first, written by Ellis, dealt with the thermal environment and its effect on the efficiency of personnel; the second, by Holling and Brokensha, dealt largely with the technical problems associated with ventilation in ships. The climatic conditions between-decks of immediate importance to the Navy, which were set out in detail in the first report and later summarized in a Hunterian Lecture (Ellis, 1953*c*), provided the climatic framework of the subsequent physiological and psychological experiments. As these experiments were concerned primarily with the problems of military personnel living and working in hot environments either between-decks or indoors, the effects of such important outdoor climatic variables as solar radiation were not examined (nor are they discussed in the chapters that follow).

At this time, too, the first major report from the workers at the National Hospital was issued (Benson, Colver, Ladell, McArdle and Scott, 1945). Work continued at the National Hospital until January, 1946, when it became necessary to dismantle the climatic chambers so that the wards occupied by them could revert to their urgently needed proper use.

The sanguine hopes of rapidly establishing the research unit at Singapore were, however, doomed to disappointment. The proposals in their original form proved unrealistic and the whole scheme might well have fallen through had it not been for the help of Dr. G. V. (later Sir George) Allen, Principal of the King Edward VII College of Medicine, and Professor R. G. Scott MacGregor, Professor of Physiology at the College. With their help a new plan for the establishment of the unit on a much more modest scale than previously proposed was evolved and this was provisionally accepted by the College authorities, the Medical Research Council and the Admiralty in April, 1946.

During 1947, the various departments of H.M. Dockyard, Singapore, proceeded with the alterations and extensions necessary to convert two animal houses, built during the Japanese occupation, into satisfactory offices and laboratories. By the beginning of 1948 the building was two-thirds completed but the air-conditioning machinery had not been delivered. In April of that year it was learned that the site of the laboratory was likely to be required for other purposes in the near future and it would be desirable for the unit to complete its experiments by the end of 1950. (In the event it was not found necessary to vacate the site until April, 1953). In the light of this new development, the Subcommittee re-examined the plans for the work at Singapore and agreed that, as the number of projects that could be handled effectively in the two-year period was limited, the unit should give first priority to validating the results of the experiments already undertaken in the United Kingdom.

The difficulties with regard to the air-conditioning machinery were overcome in the end and the Dockyard were able to announce that the work on the building and the plant would be completed by 30th September, 1948. Surgeon Commander F. P. Ellis was appointed Director of the Unit and Medical Officer-in-Charge; he arrived in Singapore on 1st September, 1948, to be followed shortly afterwards by the first members of the scientific staff, and it could be said that the Royal Naval Tropical Research Unit had come into being.

The Royal Naval Tropical Research Unit

The Unit, a Naval Civil Establishment, was the joint responsibility of the Royal Navy and the Medical Research Council. The naval Medical Officer-in-Charge acted as Director of the Unit on behalf of the Council, the Royal Naval Personnel Research Committee of the Council was responsible for the direction of the scientific work and all other responsibilities rested with the Admiralty. As an out-station of H.M.S. *Terror*, Singapore, the Unit was under the administrative authority of the Flag Officer, Malayan Area. The Admiral

Superintendent, H.M. Dockyard, Singapore, undertook the construction and maintenance of buildings, plant and equipment. Administrative, laboratory, engine-room and some of the scientific staff were appointed by the Admiralty. The Medical Research Council appointed the civilian scientists. Additional office staff, tradesmen and unskilled labour were recruited locally by the Admiralty. The Unit was an inter-service establishment to the extent that the Army co-operated by appointing two medical officers to the scientific staff, and by making available, during the latter part of the Unit's existence, volunteers from soldiers serving in Singapore and Malaya as subjects for the experiments.

BUILDINGS

Two animal houses built by the Japanese for their serum laboratories were joined together; the front half housed the administrative offices, staff rooms and a small biochemical laboratory, while the climatic chambers and the air-conditioning plant were housed in the rear half. A generous amount of space was allocated to washing and bathing facilities and there is no doubt that this was responsible in no small measure not only for the comfort, and consequently, the efficiency of the subjects and staff, but also for the almost complete absence of any form of heat dermatoses among staff and subjects.

The buildings had no architectural pretensions but functionally were quite adequate. The grounds were well laid out and in its setting of well-trimmed lawns the Unit presented a very pleasant appearance.

PLANT

There were two climatic chambers, one larger than the other, which could be used separately or together, but when they were used at the same time different conditions of temperature and humidity could not be maintained in the two rooms. In the larger, a simple form of wind-tunnel was installed in which the air in the room was made (by using a bank of single speed fans) to circulate around a small central observation room in which, for the comfort of the observers, a self-contained air-conditioning unit was fitted. In the latter part of 1950 a radiant-heat tunnel was installed in the larger climatic chamber.

The plant originally supplied was intended for erection at Bombay and was designed to produce 'any dry-bulb temperature between 75°F and 120°F with any relative humidity between 50 per cent and 90 per cent up to 95°F above which temperature the maximum dew-point temperature at which controlled conditions will be obtainable will be 95°F.' However, modifications of the plant, which increased the heat input and refrigeration capacity, considerably extended these limits both upwards and downwards (see Chapter 6). Improvisation, such as the use of water sprays within the chamber to raise the dew point obtainable or the use of ice from outside sources to add to the cooling capacity of the refrigerators in order to lower the dew point, permitted the limits to be even further extended to meet particular requirements.

In the wind-tunnel in the larger climatic chamber, the air speed was controllable over a range of 20 ft./min to 800 ft./min, but in practice speeds over 500 ft./min were not used. The lower limit was that imposed by the amount of air which had to be circulated to maintain the desired conditions of temperature and humidity. The air flow was turbulent and the velocity varied from place to place. This latter fact required accurate positioning of the subjects and special precautions to ensure (by a method of rotating the subjects to each position in turn) reasonable uniformity of treatment. Before the installation of the radiant-heat tunnel, the air speed was controlled by the use of various combinations of gauze screens and by altering the number of fans in use. Subsequently, controlling the speed of the fans by regulating the current input produced a more easily regulated and more uniform air flow. In the smaller climatic chamber no control of the air flow was possible except that which could be obtained by variation of the speed of the main circulating fan in the air-conditioning plant and by the fitting of baffles on the air inlets to the chamber.

The air removed from the chambers by the circulating fan was conveyed in a duct to the adjacent plant room where it was split. One portion passed through a water spray, the temperature of which was automatically controlled, and from this emerged with a temperature and dew point within a degree or so of the temperature of the water spray. By adjusting the proportion of the air passing through the spray and the temperature of the spray, it was possible to ensure that when this air was mixed with the air which by-passed the spray the combined air had the desired water content. Its dew point having thus been fixed, all the circulating air was passed through a bank of electric heaters to produce the desired dry-bulb temperature. There was no provision for adjusting the humidity by the admission of steam but the water spray could be used as a means for controlling the dry-bulb temperature when, for example, temperatures below that of the ambient air were required.

SUBJECTS

Volunteers for the physiological and psychological studies which were pursued concurrently at the Unit were requested from the Fleet and from establishments on the Far East Station. From these volunteers suitable men were selected to meet the requirements of the experimental programme. It was stipulated that volunteers must be in good health, have spent at least six months in the tropics and possess good conduct records. As an inducement to volunteer, special allowances were paid—1/3d. per day for petty officers, 1/0d. per day for leading and able rates, and 9d. per day for ordinary rates—and subjects were granted one day's additional leave for each complete week spent at the Unit. This pool of volunteers provided sufficient subjects for the first two and a half years. At the end of this time volunteers were sought from among Army units serving in Singapore and Malaya and these volunteers provided the subjects used in the last eighteen months of the Unit's existence. They too were required to have spent at least six months in the tropics and to meet the requirements of good health and satisfactory conduct demanded of the naval volunteers. Although the first group consisted of sailors and the second group of soldiers there was little to distinguish them, either from the standpoint of their behaviour as subjects or in their experimental results.

The naval subjects were accommodated at the Royal Naval Barracks, H.M.S. *Terror*, nearly 20 miles from the Unit, and were brought to and fro daily by bus. The Army subjects were maintained by Army units in and around Singapore and were likewise brought to and from their quarters by Unit transport.

Altogether 320 subjects were required during the Unit's existence and only an insignificant proportion of these proved unsuitable in any way. Many men who had volunteered for one series of experiments volunteered for a second. The role of subject was almost always uncomfortable, often extremely trying and sometimes even had an element of danger, and no praise is too high for the way in which these men performed their duties.

Despite the arduous nature of the experiments, absence through illness or other cause was very rare. Indeed there was no case of serious illness among the subjects and no subject suffered any serious harm through participating in the experiments. The medical standards for the acceptance of men as subjects were high. At first it was customary to reject all men who had a history of severe skin disease and all who possessed any degree of skin disease when presenting for examination. However, as time went by and the need for subjects made increasing demands on the numbers available, the requirements with regard to skin disease were relaxed somewhat, and the fear that such men might become casualties on repeated exposure to hot conditions was shown to be unfounded. Indeed many existing skin lesions healed during the subjects' participation in hot-room experiments. This is attributed to the high standard of skin cleanliness insisted upon. Adequate facilities for hot showers, clean towels, and frequent changes of freshly laundered clothing were provided. No garment was ever worn twice. It must also be pointed out that although these men spent four hours at a time in the hot room they were then able to escape to cooler conditions and allow their skins to dry. This and the cleanliness of body and of clothing were undoubtedly responsible for the very satisfactory absence of skin disease. The subjects always received a high standard of medical care. One medical officer was made responsible for the constant supervision of their health and for the treatment of their minor ills.

An example of the good health of the subjects and, perhaps, of the effects of repeated exposure to hot conditions, may be seen in the record of those who participated in the experiments known as Series III and were exposed to hot conditions six times a week from January to June, 1950. There were, in all, a total of sixteen subjects of whom four were reserves who also worked in the hot room when the others did. The reserves were not required at all for the first two and a half months of the experiments; after that time minor casualties made their services necessary, and all four were required to participate in the experiment at some time, but at no time was the experiment hindered by the ill-health of the subjects. At the conclusion of the experiment all sixteen men were as well as at the beginning, and ten of them volunteered for further experimental work. Incapacitation during exposure to heat did occur but the cases were usually ones of simple peripheral circulatory failure and on removal to a cool environment recovery was rapid.

One discipline to which the subjects were required to submit was to avoid alcohol, except in very small quantities, when engaged in experiments. Much alcohol before an experiment, even if taken eighteen hours previously, reduced the subject's ability to withstand hot conditions—presumably owing to the dehydrating effect. On the few occasions when a subject did fall from grace he had a higher body temperature and sweated less than expected and, sometimes, was unable to endure conditions which the other subjects found quite tolerable. On the whole, the subjects accepted this limitation good-naturedly and the few occasions when they defaulted sufficed to show how necessary it was.

On all occasions every precaution was taken to ensure that, as far as possible, every subject understood the nature and purpose of the experiment in which he participated.

ADMINISTRATION

The capital cost of building and equipping a climatic laboratory is high, and, despite the fact that the site of the buildings in Singapore was provided free of cost and that modifications of existing buildings rather than new buildings were required, expenditure was considerable. Details may be found in the first and final reports of the Unit (Ellis, 1949; 1953a).

The resulting anxiety to make adequate use of the equipment provided was heightened by the uncertainty regarding the time available for experimental purposes. In consequence, with a fixed programme of work to be done, special efforts had to be made to see that the climatic chambers were in constant useful employment. This in its turn produced difficulties. One of the most serious was that insufficient time remained for the adequate study, analysis and presentation of the results as they became available. Another was that of meeting the requirements of the two separate sections of the Unit—the physiological and the psychological. Up to the last year of the Unit's existence, the use of the experimental facilities was about equally divided between the two. This division of the facilities, which required a considerable amount of preliminary planning, often produced minor administrative problems. However, these never proved insurmountable and it was amply demonstrated that it is possible for more than one group of workers to use the same hot-room facilities satisfactorily.

In the proposals for the establishment of the Unit at Singapore which were finally adopted by the Admiralty and the Medical Research Council, it was laid down that:

> 'The Principal of the King Edward VII College of Medicine, Singapore, agrees, subject to the approval of the Council of the College, with the proposals and arrangements for research on the effects of climate on psychological and physical efficiency of personnel serving in the tropics which are defined in this memorandum, to be carried out by the Tropical Research Unit in the College of Medicine, Singapore, provided that the Unit whilst working in the College of Medicine should come under the general administration of the Council and the Principal of the College. The Principal will make arrangements for the co-ordination with other departments of the College when such co-ordination is required.'

This formal enunciation of the relations which were to exist between the University of Malaya on the one hand and the Unit on the other gives no hint of the warm spirit of co-operation which existed in practice. Members of the University shared in the research programme of the Unit and the staff of the Unit participated in the teaching programme and examinations of the University. Besides these official relations, there was always a good deal of personal goodwill between the members of the University Department of Physiology and the staff of the Unit. Nor was this goodwill confined to the Department of Physiology. It was extended by the University as a whole which, among other things, housed, as though they belonged to its own staff, two of the civilian members of the Unit—a fact which is remembered with gratitude by those concerned—and invited the Unit to share to the full the corporate life of the University.

CHAPTER 2. A PRELIMINARY STUDY IN THE TROPICS OF THE EFFECTS OF AIR TEMPERATURE, HUMIDITY AND AIR SPEED ON NATURALLY ACCLIMATIZED MEN

An account of the work of J. M. Adam, F. P. Ellis, J. O. Irwin, M. L. Thomson and J. S. Weiner

The Experiments of Series I

When the task of embodying the results of the physiological work done at the Royal Naval Tropical Research Unit in a single comprehensive report was undertaken, it was realised that an adequate understanding of this work required a knowledge of that previously done by the team of workers at the National Hospital for Nervous Diseases, London, under the direction of Dr. E. A. Carmichael. As no account of these earlier experiments has been published a fairly extensive account, based on the reports of the workers concerned, is given in the appendix to this report (p. 280 *et seq.*). From the results of these experiments the London workers concluded that as a measure of environmental stress the Effective Temperature Scale was deficient in certain respects and a new index, the Predicted Four-Hour Sweat Rate (P4SR), was devised empirically from the experimental results. This index is also described in detail in the appendix.

For various reasons, as the London workers were careful to point out, the conclusions that were drawn from these early experiments could be considered to be only of a tentative nature. With the establishment of the Tropical Research Unit at Singapore it was possible to put in train a succession of experiments designed to test their validity when applied to men living and working in a tropical environment.

The objectives of the experiments conducted at Singapore were, essentially, as follows (Ellis, 1949):

1. To investigate in the tropics the ability of men to withstand various combinations of:
    (a) different levels of air temperature, humidity, air speed and mean radiant temperature;
    (b) different types of clothing;
    (c) different rates of energy expenditure, and
    (d) different periods and intervals of exposure to these conditions.
2. To compare the state of acclimatization of 'naturally acclimatized' men on the Far East Station with that of the 'artificially acclimatized' men who participated in the experiments at the National Hospital, London.
3. To assess the value of the Effective Temperature Scale for grading the severity of thermal conditions encountered in the tropics.
4. To estimate the 'predictive' accuracy of the P4SR Index.
5. To define acceptable upper limits of warmth in the compartments of warships for the different forms of activity in which men are engaged at sea.

The first group of experiments—referred to as Series I—which has been described in full by Adam, Ellis, Irwin, Thomson & Weiner (1952) under the title 'A preliminary study to determine the effects of exposure for four hours twice weekly to varying combinations of air temperature, humidity and air movement', forms the subject of this chapter. This group of experiments was intended in particular to demonstrate whether or not the conclusions of the workers at the National Hospital, based as they were on highly and artificially acclimatized subjects, were applicable to men in the 'natural state of acclimatization', i.e. to men possessing the ability to withstand the effects of hot environments that is produced by a period of residence in the tropics.

METHODS

Experimental Plan

The original plan of these experiments was to have twenty-four climate combinations—all combinations, in fact, of air speed at four levels, dry-bulb temperature at three levels, and wet-bulb temperature at two levels. These climate combinations were to be randomized separately for each of three teams with four persons in each. They were to be combined with four 'postures' or work-clothing combinations—(a) 'shorts working', (b) 'shorts resting', (c) 'overalls working', (d) 'overalls resting'—according to the following scheme.

Climate combinations (randomized for each team)	Work-clothing combinations Persons randomized			
	1	2	3	4
I	a	b	c	d
II	b	a	d	c
III	c	d	a	b
IV	d	c	b	a
V	a	c	b	d
VI	b	d	a	c
VII	d	b	c	a
VIII	c	a	d	b
IX	a	d	b	c
X	d	a	c	b
XI	b	c	a	d
XII	c	b	d	a
XIII	a	b	d	c
XIV	b	a	c	d
XV	c	d	b	a
XVI	d	c	a	b
XVII	a	c	d	b
XVIII	b	d	c	a
XIX	d	b	a	c
XX	c	a	b	d
XXI	a	d	c	b
XXII	d	a	b	c
XXIII	b	c	d	a
XXIV	c	b	a	d

In this plan all separate climate and posture comparisons were unconfounded with differences between persons and were, therefore, equivalent to comparisons on the same person. The error term contained such climate-posture interactions as were not confounded with personal differences. In testing the climate-posture interactions it was proposed to ignore differences between persons within teams. It was not realized that these interactions were as important as, in fact, they proved to be.

For various reasons this experimental plan was not used in its original form.

Instead it was decided to investigate the effects of three levels of dry-bulb temperature (90, 100 and 120°F), four levels of wet-bulb temperature (80, 83, 85 and 88°F), four levels of air speed (40, 100, 300 and 500 ft./min) and the four work-clothing combinations, but not all combinations of these factors. The effects of two dry-bulb temperatures, 90 and 120°F, were examined at all combinations of the two wet-bulb temperatures 80 and 85°F and all four air speeds, but at two wet-bulb temperatures, 83 and 88°F, at only one air speed, 300 ft./min. The effect of one dry-bulb temperature, 100°F, was examined at all four levels of wet-bulb temperature, 80, 83, 85 and 88°F, at only one level of air speed, 300 ft./min. This produced a total of twenty-four combinations of dry-bulb temperature, wet-bulb temperature and air speed:

Dry-bulb temp. (°F)	Air speed (ft./min) Wet-bulb 80°F	Wet-bulb 83°F	Wet-bulb 85°F	Wet-bulb 88°F
	40	—	40	—
	100	—	100	—
90	300	300	300	300
	500	—	500	—
100	300	300	300	300
	40	—	40	—
	100	—	100	—
120	300	300	300	300
	500	—	500	—

To these combinations the roman numerals I–XXIV were allocated, and they were classified into two groups of twelve according to whether they were considered to be 'moderate' or 'severe' in their effects.

The four work-clothing combinations produced by 'resting' and 'working' in overalls and 'resting' and 'working' in shorts can be arranged in twenty-four different orders. One of these orders was assigned to each of the twenty-four climate combinations in accordance with the scheme shown on p. 12. The twelve subjects to be used in the experiments were divided, on the basis of the results of a uniformity trial ('dummy' experiment), into four grades of rate of sweating, and three teams were constituted by choosing for each team one man from each grade. The four members of each team were numbered from 1 to 4 and the work-clothing combination for each man for each climate combination was thus determined.

The chronological order in which each of the twenty-four climate combinations was examined was determined by lot separately for each team, subject to the proviso that severe and moderate conditions alternated.

One of the chief requirements of these experiments was that the natural state of acclimatization of the subjects should be maintained as far as was possible. The number of hot-room exposures was therefore limited to two per week for each man. There were three four-man teams, and each week each team was exposed to one 'severe' and one 'moderate' environment. One exposure in each week was in the morning and one in the afternoon. This last arrangement was imposed by the necessity for sharing the hot-room facilities with the workers in applied psychology.

Control of Environmental Conditions

The climatic chambers have been described in Chapter 1. This series of experiments was conducted in the larger of the two chambers—that in which the rate of air flow could be controlled.

The temperatures of the walls and surroundings were maintained as near to the dry-bulb temperature of the air as possible, but differences of 3°F between globe- and dry-bulb temperature occurred at times at the highest air temperatures. During experiments involving high air speeds, the dry-bulb temperatures in the two test sections of the chamber sometimes differed from each other by as much as 4°F. However, temperature recordings were taken at 5 min intervals in both rooms with shielded Assmann psychrometers, and the temperatures were controlled to provide an average temperature for the two sections which agreed with the target temperature for the experiment. The average temperatures maintained were usually well within 1°F of the target dry- and wet-bulb temperatures for any single reading, and for a four-hour experiment the average temperature was always within 0·02°F for the 100 measurements taken in the two rooms.

The wind tunnel had single speed fans. The air speed was adjusted to the desired value by varying the number of fans in use, fitting to them various baffles and gauze covers, and resetting the angle vanes and the louvres of the air inlets. However, when at the end of the series the air speeds in the two compartments were carefully surveyed with the silvered katathermometers, the following wide variations in speed were found for each target figure (ft./min):

Target...		40	100	300	500
Achieved ...	Mean	44	86	313	522
	Range	(19–100)	(20–180)	(100–450)	(210–680)

The variations in temperature and air speed in the different positions and between the two test sections were offset, as far as possible, by moving the subjects from chair to chair at given intervals and by changing the groups over between the two test sections so that they experienced similar environmental conditions during the four-hour experimental period.

Subjects

The subjects and their reserves were fifteen fit young naval ratings who volunteered from ships or shore establishments on the Far East Station. Most of the subjects spent 2 months in Singapore before the trials commenced, owing to a delay in the completion of the plant. Their average period of service in the tropics during the commission they were then serving was 16·7 months (range 12–20 months). Their physical characteristics were:

	Mean	*Range*
Age (yr)	23	19 – 30
Height (cm)	171·6	163·8 –184·7
Weight (kg)	64·10	54·55– 75·91
Surface area (m²)	1·75	1·58– 1·99

These accorded well with those of the subjects used at the National Hospital (p. 281).

Experimental Procedure

The four-hour experimental procedure adopted was basically that used by Dunham and his co-workers in their experiments at the National Hospital, London (Dunham, Holling, Ladell, McArdle, Scott, Thomson and Weiner, 1946).

The subjects entered the test rooms at 2-min intervals at the commencement of each experiment and left in the same manner when it was completed. The routine for 'working' subjects (the 'Queen Square Routine' of Dunham *et al.*) was as follows:

Time (min)	*Activity*
0 – 10	Subjects enter chamber, weighed naked; don weighed clothing
10 – 40	Step-climbing*
40 – 70	Rest, seated
70 – 100	Step-climbing*
100 – 130	Rest, seated
130 – 160	Step-climbing*
160 – 220	Rest, seated
220 – 240	Step-climbing*
240	Subjects weighed naked and leave chamber; clothes weighed

*On stools 12 in. high, 12 times per minute.

The 'resting' subjects sat in upright wooden chairs with canvas backs and seats throughout the four-hour period except when changing seating positions, being weighed or standing to have pulse rates recorded. These subjects and their clothes were weighed at the same time as the 'working' subjects.

The two kinds of clothing worn in the experiments were 'shorts' and 'overalls'. The former consisted of white drill shorts and leather sandals, the latter of the standard naval single-piece blue drill overalls worn over light-weight shorts, and leather sandals. All subjects wearing 'shorts' wore sweat-collecting envelopes on their left arms for the first 100 min of each experimental period.

A 0·1 per cent solution of sodium chloride at a temperature of about 80°F was available in unlimited quantities for the subjects to drink if they wished.

The outstanding differences between the conditions of the experiments of Series I and those of the experiments of Dunham *et al.* (1946) in London were: (a) in nearly all of the London experiments subjects wearing overalls wore shorts of heavy drill underneath but in Singapore subjects in overalls wore light-weight shorts underneath; (b) the London subjects drank unsalted water, but the Singapore ones drank saline; (c) the London subjects in shorts did not wear the sweat-collecting envelopes worn by the Singapore subjects in shorts for the first 100 min.

Rectal temperatures (measured with mercury-in-glass clinical thermometers) and 'sitting' and 'standing' pulse rates (counted at the wrist) were recorded at regular intervals. The loss of sweat during each four-hour experiment ('total' sweat loss) was obtained from the weight loss after adjustment for intake of fluid, losses in the breath being neglected. 'Evaporated' sweat loss was taken to be the difference between total sweat loss and sweat remaining in the clothes at the end of the trial, 'drippage', which in hot humid conditions was often considerable, being neglected.

The efficiency of the subjects at the end of each experiment was assessed by the subjects and the observers on the following scale (that used by Dunham *et al.*):

0. Unaffected by work and heat
1. Perfectly able to continue work
2. Able to finish work and still efficient, but doubtful whether efficiency could be maintained for a further 10 min
3. Able to finish work, but work done inefficiently
4. Unable to finish work
5. Collapse

Each subject also indicated the sensation of warmth he experienced during the trial on the following scale: A comfortable; B comfortably warm; C too warm; D far too warm.

Uniformity Trials

Uniformity trials ('dummy' experiments) to detect changes in the state of acclimatization of the subjects were carried out before (one trial) and after (two trials) the main series of experiments. The procedure was that of the main experiments with the subjects 'working', wearing shorts and sandals, and with sweat-collecting envelopes on their left arms. The environment for the three uniformity trials was dry-bulb temperature 90°F, wet-bulb temperature 86°F, and average air speed 50 ft./min.

RESULTS

Variations in the Subjects during the Series

Between Subjects

The rectal temperatures and pulse rates at the beginning of each experiment showed a highly significant variation between individuals (Table 1). This difference between subjects is a constant finding and is characteristic of all such measurements.

Between Morning and Afternoon Experiments

The average initial rectal temperature and pulse rate were 0·44°F and 1·9 beats/min higher in the afternoon than in the morning. These differences, which are highly significant for initial rectal temperatures and approach the 5 per cent level of significance for initial pulse rates, were not expected when the trial was planned. The 24 treatments, however, had been arranged in a random order for each team, and in so far as this order was maintained no bias was introduced by these unsuspected differences in the estimates of treatment comparisons although the precision of comparisons would be reduced; however, some re-arrangement of experiments was necessitated by plant failure, so that the experiments for two environments were all carried out in the morning.

Between the Earlier and Later Parts of the Series

The average initial rectal temperature was 0·1°F higher for the period 19th January to 17th March than for the period 25th March to 28th April; this difference is significant at the 5 per cent level.

In Acclimatization

Comparison of the total sweat losses in the pre-series uniformity trial and the two post-series trials showed that the sweat loss was 413 g greater in the second, and 349 g greater in the third, than in the first trial. Similarly, it was observed that the average final rectal temperature was 0·26°F less in the second, and 0·54°F less in the third, than in the first trial (Table 2). Furthermore, the average concentration of 'arm-sweat' sodium chloride for the group fell steadily during the first 2 months of the experiment as the weather grew warmer, although the average concentration rose again after this to reach practically the pre-series level by the end of April. According to these criteria the subjects were more acclimatized at the end of the series than they were at the beginning, and it is possible that their level of acclimatization was even greater in the middle of the trial than it was at the end.

These changes in level of acclimatization could have been due either to the repeated exposure to hot-room conditions twice a week throughout the period, or to changes in the climatic conditions in Singapore to which the subjects were exposed for the remainder of the week. It is probable that both factors were involved to some extent.

The monthly averages of the daily maximum and of the daily mean air temperatures at Singapore rose from January to March and then declined. The change in maximum air temperature—from 87·8°F to 90·1°F—was not great; this difference would be unimportant in a temperate climate. It might, however, be of some importance at the level of temperature occurring at Singapore, and might make all the difference between reasonably comfortable conditions and uncomfortably warm conditions with marked sweating.

To summarize, it would seem, therefore, that at the end of the trials the subjects were, on the average, more acclimatized than they were at the beginning, and that the average level of acclimatization may have fluctuated during the series. These changes were probably mainly due to the bi-weekly experimental exposures, but may have been due in part to changes in the Singapore climate. The position is further complicated, however, by the fact that defects in the plant (in the middle of the series) interrupted the regular and uniform exposure of the subjects to hot conditions in the climatic chambers.

The Response to Variations in the Environmental Factors

The alterations introduced into the original plan of the experiment created considerable difficulties in the analysis of the results. These were overcome by dividing the results into two sections. Section A consisted of all combinations of dry-bulb temperatures 90 and 120°F, wet-bulb temperatures 80 and 85°F, and air speeds 40, 100, 300 and 500 ft./min. Section B consisted of all combinations of dry-bulb temperatures 90, 100 and 120°F and wet-bulb temperatures 80, 83, 85 and 88°F at one air speed, 300 ft./min. It will be noted that the combinations of dry-bulb temperatures 90°F and 120°F with wet-bulb temperatures 80°F and 85°F at the third air speed, 300 ft./min, occurred in both Section A and Section B.

The results for these two sections were analysed separately. Where necessary, the individual results were corrected for differences between subjects by analysis of covariance on the basis of the results of the uniformity trial held before the beginning of the experiment proper. A complete analysis of variance of each variable was carried out for each of the two sections. The mean values for every effect or interaction of effects which was significant were then tabulated and studied in relation to their standard errors.

Sweat Loss

Three aspects of the sweat loss were examined—total sweat loss, sweat loss per square metre of body surface area, and evaporative water loss.

The results of the analysis of total sweat loss are set out in Tables 3 and 4. The principal conclusions were as follows:

1. On the average, the sweat loss was a little greater when the wet-bulb temperature was 85°F than when it was 80°F, and very much greater when the dry-bulb temperature was 120°F than when it was 90°F.

2. On the average, as the air speed increased the sweat loss tended at first to decrease and then to increase. This was also true whether the wet-bulb temperature was 80°F or 85°F. It was also true at dry-bulb temperature 120°F, but at dry-bulb 90°F the decrease persisted up to an air speed of 500 ft./min.

3. The excess of the sweat loss of the working subjects over that of the resting subjects was the only average direct work-clothing effect that was significant. It was a little greater for men in overalls than for those in shorts.

4. When the air speed was 300 and 500 ft./min the average sweat losses for men in shorts were greater than for those in overalls provided the dry-bulb temperature was 120°F[*], but when it was 90°F the reverse was true. The 'crossing-over' point was below dry-bulb 100°F for resting subjects but higher for working subjects, for whom it depended partly on the level of the wet-bulb temperature. At the two lower air speeds, 40 and 100 ft./min, the sweat loss was higher for men in overalls than for men in shorts at both 120°F and 90°F dry-bulb temperature.

5. When the air speed was 300 ft./min (Section B), the average sweat loss of the working subjects was greater for those in overalls than for those in shorts at all four wet-bulb temperatures, and increasingly so as the dry-bulb temperature rose. For resting subjects it was less if they wore overalls than if they wore shorts, except for the dry- and wet-bulb temperatures of 90°F and 88°F where it was about the same.

6. There were certain anomalous values. With the '120°F/85°F/100 ft./min working' combination, the sweat loss of men wearing shorts was below that of those in overalls to a greater extent than would have been expected; and with '120°F/80°F/40 ft./min resting' and '120°F/85°F/40 ft./min working' the sweat losses of men wearing shorts and overalls were about the same, though a greater loss for those in overalls would have been expected. These effects might have been due to differential acclimatization owing to the spacing of the trials.

These conclusions may be summarized as follows. In general, men sweat more when they wear overalls than when they wear shorts. The position is reversed, however, when the dry-bulb temperature is 120°F, provided the air speed is sufficiently high. The level of air speed where this reversal occurs is about 300 ft./min but it varies with the wet-bulb temperature and the degree of activity of the subject.

The results of the analysis of sweat loss per square metre of surface area were very similar to those of the analysis of total sweat loss.

The analysis of evaporative water loss showed that this loss was a little greater in shorts than in overalls, probably because more water can be retained in overalls. Otherwise the results conformed to those for total sweat loss and need not be considered further.

Rectal Temperature

The results for the final rectal temperature were examined in exactly the same way. The effects are set out as tables of mean values in Tables 5 and 6. It was found that the final rectal temperature increased as the dry-bulb or the wet-bulb temperature rose, but the effect of humidity was greater at the higher air temperature. The final rectal temperature was higher for working than for resting subjects, and the difference between the two groups increased as either the air temperature or the humidity increased but decreased with increasing air speed. When the air speed was 300 ft./min (Section B), the final rectal temperature of men wearing shorts was higher than that of men wearing overalls at 120°F, but not at 90°F or 100°F. There was a similar effect averaged over all air speeds; the final rectal temperature of men in shorts was less than that of men in overalls when the air temperature was 90°F, but when the air temperature was 120°F there was no difference.

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[*] This was true at 500 ft./min for working and resting subjects separately. It was true for working subjects at 300 ft./min if results for wet-bulb temperatures 80 and 85°F only were included in the average (though the difference was very small), but not if those for all four wet-bulb temperatures were included. It was true for resting subjects at 300 ft./min.

Pulse Rate

The final pulse rate, recorded in the standing position at the end of the experiment, increased on the average with increases in air temperature and humidity, but increased more with the wet-bulb temperature at the higher dry-bulb temperatures (Tables 7 and 8). It was higher for working than for resting subjects, and the difference between these two groups was greater at the higher dry-bulb temperatures.

When the dry-bulb temperature was 120°F and the air speed 40 ft./min the final standing pulse rate was higher for men in overalls than in shorts. This difference diminished with increasing air speed and reversed its sign at an air speed of 500 ft./min, but this positive difference was not significant. When the dry-bulb temperature was 90°F there were no significant differences but a similar pattern was present.

The pattern shown by the effects of climate on body temperature and heart rate was similar to that shown by the effects on sweating. In particular, the 'crossing-over' of the curves for men wearing shorts and men wearing overalls at dry-bulb temperature 120°F when the air speed was 300 ft./min or 500 ft./min, observed in the case of the sweat loss, which suggested that further increases of air speed would have adverse rather than beneficial effects, was also observed for the rectal temperature and pulse rate.

Comfort and Efficiency

Inspection of the data alone made it clear that the comfort and efficiency ratings were not of much diagnostic value in distinguishing the effects of the different climate combinations, particularly for resting subjects. However, these ratings were analysed for working subjects. The efficiency gradings 0 to 5 (p. 15) were regarded as numerical measures and the comfort gradings (p. 16) were treated in the same way by taking A=0, B=1, C=2, D=3.

Both comfort and efficiency were reduced, on the average, with increasing air temperature or increasing humidity. When the dry-bulb temperature was 90°F there was little change in efficiency with air speed, at wet-bulb temperatures of either 80°F or 85°F. When the dry-bulb temperature was 120°F, the highest and lowest air speeds were more comfortable when the wet-bulb temperature was 80°F, while at wet-bulb 85°F comfort was increased more or less steadily with increasing air speed. This last result—a somewhat complex interaction between wet- and dry-bulb temperatures and air speed—must not be stressed too much in view of the approximate nature of the gradings.

Comparison with Results Obtained in London

An important objective of this series of experiments was to compare the state of acclimatization—the ability to withstand heat stress—of 'naturally acclimatized' men in the tropics with that of the 'artificially acclimatized' subjects used in the experiments at the National Hospital in London. The conditions of the experiments were different in the two cases; the London subjects were exposed daily to the test conditions and were trained to work under these conditions before the experiments commenced, whereas those in Singapore were exposed only at three-day intervals and had no previous training. Thus an important point under investigation was whether the highly acclimatized men in London who worked for four hours daily at high temperatures during the experiments but spent the remainder of the 24 hours in the ordinary English climate, were more or less able to withstand the stress of working at high temperatures than the men in Singapore who were not artificially acclimatized before the experiment and were exposed only twice a week to hot room conditions, but who lived for the remainder of the week in a warm humid climate.

Sweat Loss

The exact environments used in London were repeated in only a small number of experiments in Series I. However, the nomogram for the prediction of the four-hour sweat rate of the 'artificially acclimatized' subjects in London had been constructed empirically from the results of the London experiments. The P4SR values for all the environments used in this series were therefore obtained from the nomogram constructed from the London results and compared with the values for total sweat losses actually observed in the Singapore experiments, using the observed metabolic rates of 48 and 100 $\text{kcal.m}^{-2}.\text{hr}^{-1}$ for resting and working men.*

The total sweat losses obtained in Series I were compared with the P4SR values by the following method. There were available 64 climate-work-clothing combinations in Section A, and 48 in Section B. The regression of y on x was calculated for each section separately. The regression lines proved to be

$$\text{Section A: } Y = 2{\cdot}047 + 0{\cdot}9783\,(x - 1{\cdot}968)$$

$$\text{Section B: } Y = 1{\cdot}957 + 0{\cdot}9248\,(x - 1{\cdot}890)$$

where y = corrected mean total sweat loss (litres) and x = P4SR value from the nomogram. These two lines agree well; they do not differ significantly in position or slope. They both yield positive but small values for the observed total sweat loss when the P4SR is zero (122 ± 46 g and 209 ± 39 g). Had the two lines been assumed to go through $x = 0$, $y = 0$, the slopes would have been 1·023 and 1·006. Thus, on the average, the observed total sweat loss and the predicted four-hour sweat loss agree closely. The overall correlation between them is 0·96.

This overall agreement is very striking and it is important to consider its meaning. The P4SR (for given clothing and work) is a function of climate, notwithstanding that it has been expressed in the form of a nomogram instead of in the form of a series of mathematical equations. If its sole object were to predict the *average* physiological behaviour of a *large group of subjects* in a hot room under controlled conditions, it would be hard to find a better substitute. There is, on the one hand, a series of climate variates such as wet-bulb and dry-bulb temperatures and air speeds, and on the other a series of physiological variates such as sweat losses, pulse rates and rectal temperatures. Whatever function of the former and of the latter were selected, the correlation of the two could scarcely be improved, for it is already 0·96; but it is important to realise that this correlation takes no account of variation from one subject to another. This correlation coefficient of 0·96 is reduced to about 0·93 when individual variations are taken into account.†

It is perhaps remarkable that the behaviour of the Singapore subjects was so similar to that of the London subjects. Nevertheless, there were significant differences for particular treatment combinations.

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* But see Chapter 4.

† The value of the P4SR Index as a measure of environmental stress is discussed in later chapters.

An analysis of variance was performed on the deviations from regression (Table 9) so that it was possible to see for which treatment combinations departures from the expected values were significant and to examine all such effects.

Separate climate and work-clothing effects. Only those direct climate effects involving changes in air speed appeared to be significant. These, however, were average effects, and the relative effects of variations in wet- and dry-bulb temperatures were not the same at different air speeds. The most important direct effect was the difference between wearing shorts and wearing overalls. On the average, the sweat loss of the men wearing shorts was greater and the sweat loss of those in overalls was less than that expected from the nomogram. Also, the sweat loss of the working subjects was greater and that of resting subjects less than that expected. It must be remembered that these were averages of work-clothing effects which differed at the different climate levels, and were therefore examined separately at each level.

Climate work-clothing interactions. When the subjects were *resting* at a dry-bulb temperature of 90°F there were no striking departures from the nomogram at any air speed at either 80°F or 85°F wet-bulb temperature. When the dry-bulb temperature was 120°F the situation was different. For both wet-bulb temperatures 80°F and 85°F the sweat loss of men wearing shorts was less than expected at the two lower air speeds and equal to, or greater than that expected at the two higher speeds; the sweat loss of those in overalls was always lower than expected at all air speeds (apart from the anomalous value at 120°F/85°F/40 ft./min).

When the subjects were *working* at the dry-bulb temperature of 90°F the sweat loss of those in shorts was greater than expected, but the difference decreased with increasing air speed; the sweat loss of men in overalls was less than or equal to that expected, and the deficiency became greater with increasing air speed (the value +211 at wet-bulb 85°F was not significantly different from zero).

When the dry-bulb temperature was 120°F the sweat loss of men wearing shorts was again greater than expected, and when the wet-bulb temperature was 80°F the excess increased with increasing air speed. This seemed also to be the tendency when it was 85°F though the value at 40 ft./min air speed was anomalous. For those wearing overalls the sweat loss at 80°F wet-bulb temperature was greater than expected at 40 ft./min air speed, but less than expected at the three higher air speeds. At wet-bulb 85°F there was a similar but more irregular tendency.

The difference between the total sweat losses of men wearing shorts and of those in overalls when the dry-bulb temperature was 120°F increased with increasing air speed when the wet-bulb temperature was 80°F or 85°F, and this was the most noteworthy effect of all.

The average difference between the sweat loss of working and resting subjects did not vary much with climate. When the dry-bulb temperature was 90°F, the differences in the excess of the sweat loss over expectation diminished with increasing air speed. This was also true when it was 120°F and the wet-bulb was 80°F, but when the wet-bulb was 85°F there was no consistent trend with air speed.

Further comparisons. The additional observations made at wet-bulb temperatures of 83°F and 88°F and an air speed of 300 ft./min (Section B) confirmed the conclusions set out above.

Rectal Temperature

The rectal temperatures of the Singapore subjects for six environments were compared directly with those of the London subjects given in the paper by Dunham *et al.* (1946), and those for all environments were compared with the predicted figures calculated from the P4SR values.

Direct comparison. This was possible for the six combinations of dry-bulb temperatures 90, 100 and 120°F with wet-bulb temperatures 83 and 88°F at the single air speed of 300 ft./min. For these combinations the average final rectal temperature of the subjects at Singapore (100·1°F) was 0·6°F higher than that of the London subjects (99·5°F)—1·0°F higher for working subjects and 0·4°F higher for resting subjects. The same average final rectal temperatures for men wearing shorts and men wearing overalls were observed both at London and at Singapore. The rectal temperature of the men wearing shorts at Singapore was, however, above that of those wearing overalls when the dry-bulb temperature was 120°F and below it when the dry-bulb temperature was 90°F or 100°F. The difference between the average final rectal temperature of working men and that of resting men over this limited range of environmental conditions was 1·3°F at Singapore and 0·7°F at London.

Comparison with values predicted from the P4SR nomogram. Predictions were made from the formula

$$Y = (0{\cdot}4 \times \text{P4SR}) + 98{\cdot}7$$

where y is the final rectal temperature in °F. The average final rectal temperature predicted by this formula for all 24 environments was 99·5°F, which is 0·6°F less than the observed value, 100·1°F. The value predicted for the 6 environments at air speed 300 ft./min—which were used both in London and in Singapore—was also 99·5°F, which agreed with the value observed for them in London, but was again 0·6°F lower than their observed value in Singapore (100·1°F). It is interesting to note that the formula predicts the same value for the 6 climates as for the 24; as the observed values in Singapore for the 6 and the 24 were also the same, it would seem that the value predicted for the 24 climates (99·5°F) would have been observed in London had they all been used in the experiments there.

Pulse Rate

Comparison of the Singapore results with those observed by Dunham *et al.* (1946) in the six experiments which were directly comparable showed that the average pulse rate for those six conditions was 5 beats/min higher at Singapore than at London. In both series of experiments working caused an increase in pulse rate of about 30 beats/min above the resting value. The average pulse rate was approximately the same for men wearing overalls at Singapore, for men wearing shorts at Singapore and for the London subjects wearing overalls. The London subjects when wearing shorts, however, had a pulse rate 7 beats/min slower. Increasing the dry-bulb temperature from 90°F to 120°F resulted in an average increase of 20 beats/min in the London subjects and 27 beats/min in the Singapore subjects. When the wet-bulb temperature was 83°F the average value for the two series was approximately equal, but when it was 88°F the average value for the Singapore subjects was 7·5 beats/min higher than for the London subjects.

Levels of Stress at which Subjects Failed to Complete Experiments

In Table 10 are set out the environments, together with the work-clothing combinations, at which one or more of the subjects failed to complete the four-hour exposure in the Singapore experiments and in the London experiments of Dunham *et al.* (1946). One subject at Singapore failed at an environment of which the P4SR was 3·1. The lowest value of the P4SR at which a subject failed at London was 4·35, but if the single exceptional case at Singapore is neglected it will be seen that the conditions under which failure occurred were very similar for both groups of men. The point at which failure occurred was represented in both groups by environments having a P4SR value of approximately 4·5. Above this value failures could be expected in increasing numbers as the stress of the environment increased; below this value failures in either group would not be expected.

Urinary chloride determinations indicated that salt deficiency was not usually a factor contributing to heat incapacitation under these conditions. Dehydration was not marked; the maximum loss of weight (water deficit) up to the time of failure to continue with the work was about 3 per cent of the body weight, but the rate at which this loss occurred may well have aggravated the onset of syncopal symptoms in susceptible individuals. The most common diagnosis was heat syncope or peripheral circulatory failure.

Comparison of the Observed Sweat Losses with those Expected from the Effective Temperature Scale

Total sweat loss, as a measure of environmental stress, was compared with the Effective Temperature Scale by the method used for the comparison with P4SR values. The 'Basic' Effective Temperature Scale was used for subjects in shorts and the 'Normal' Scale for subjects in overalls. The two regression lines were found to be

$$\text{Section A:}\quad Y = 2047 + 208{\cdot}4(x - 86{\cdot}50)$$

$$\text{Section B:}\quad Y = 1957 + 209{\cdot}6(x - 86{\cdot}05)$$

where y = corrected mean total sweat loss and x = effective temperature.

The results for Sections A and B agreed closely, but whereas the regression coefficients on P4SR had standard errors of 3·6 per cent and 2·0 per cent respectively, the corresponding figures for effective temperature were 10·0 per cent and 9·3 per cent.

The overall correlation of observed total sweat losses with predicted losses (P4SR) was 0·96, but with effective temperature it was only 0·78 (0·80 if parabolic regression was used). (The reduced correlation was largely due to the fact that effective temperatures make no allowance for differences in rates of energy expenditure.) Thus the deviations of total sweat losses from the values expected if effective temperature is used as an index of stress under these warm conditions are considerably greater than if P4SR is used.

Analysis of variance of the deviations from regression showed that all work-clothing effects and most of their interactions with climate effects were significant. In contradistinction to the results for P4SR, the direct climate effects were large and much more important than the interactions (Table 11).

The most important direct effect was the difference between working and resting subjects. The average sweat rate for the former was decidedly greater, and for the latter decidedly less, than that expected from regression on effective temperature; and the magnitude of the effect did not vary significantly with climatic conditions. As the Effective Temperature Scale was originally designed for persons engaged in light activity, this is not surprising. There was also a small but significant difference between the departures from expectation for men wearing shorts and for those wearing overalls which, as might be expected, was a little greater in the results for working than in those for resting subjects.

On the average, the sweat loss was above expectation when the wet-bulb temperature was 80°F *and below when it was* 85°F. When the air speed was 300 ft./min, the sweat loss was above expectation at a wet-bulb temperature of 83°F and below at 88°F, except at the combination '120°F/88°F' (where it was above). The sweat loss of men exposed to '120°F/88°F' was greater than anticipated whether P4SR or effective temperature was used to predict the effect.

On the average, the sweat loss was above expectation when the dry-bulb temperature was 120°F *and below when it was* 90°F. When the air speed was 300 ft./min it was below expectation at 100°F. On the average, the sweat loss was above expectation when the air speed was 300 and 500 ft./min, and below when it was 40 and 100 ft./min.

The amount of departure from expectation varied more with air speed when the wet-bulb temperature was 80°F than when it was 85°F, and when the dry-bulb temperature was 120°F than when it was 90°F. At dry-bulb 120°F, but not at 90°F, the sweat rate was above expectation at the lowest air speed.

Comparison of the Results of Series I with Effective Temperature and with the P4SR Index

McArdle & Dunham, Holling, Ladell, Scott, Thomson, Weiner (1947) stated that 'It is readily apparent that the P4SR is distinctly superior to the Effective Temperature Scale with regard to the closeness of fit of both sweat rate, final rectal temperature and "fitness" and "comfort" grading, even allowing for the curved pattern of response to increasing effective temperature, the different response to the two levels of metabolism, and the two types of clothing'. The results of Series I, however, did not support this contention. They showed that the P4SR nomogram predicted the physiological effects of hot environments more accurately than the Effective Temperature Scale only if the effects of work rate (rate of energy expenditure) and clothing were ignored. This is made plain by the results set out in Table 12, in which the average correlations within the four work-clothing groups are contrasted with those for all four groups combined.

The correlation coefficient between total sweat loss (corrected mean values) and effective temperature over all 96 climate-work-clothing combinations is 0·8 (not allowing for non-linear regression it is 0·78). That between the P4SR Index and total sweat loss is 0·96, but if the 'within group' correlations are compared, that for effective temperature (0·93) is only slightly less than that for the P4SR Index (0·98). In the case of final rectal temperature and pulse rate, the 'within group' correlation for effective temperature is superior to that for the P4SR Index. If separate regression equations for working and resting subjects are calculated for the P4SR Index, the two regressions form one line; for effective temperature there is a difference in position but not in slope. For effective temperature the combined correlation is considerably lower than that of the average within groups, but this is because numerically equal effective temperatures do not mean the same thing for working and resting subjects, nor do they mean the same thing on the 'Basic' and 'Normal' Scales.

The correlations of the results of the Singapore experiments do not, therefore, support the conclusions of McArdle *et al.* (1947). In fact, effective temperature, when correctly used, can be said to have nearly as much predictive value as the P4SR, although it cannot be regarded as a comprehensive scale in the same sense as the P4SR. To that extent, the P4SR Index provides a better measure of stress for conditions such as those investigated.

The Series I results do, however, support certain of the criticisms of the Effective Temperature Scale made by the workers at the National Hospital—for example, that it fails to indicate the effects of changes in air speed on the stress imposed by the environments. In particular, the sweat losses in this series tend to support the findings of Dunham *et al.* (1946), and not the Effective Temperature Scale; the latter is almost linear in relation to increasing air speed and indicates, therefore, continuous uniform improvement in conditions with increasing air speed. Contrary, however, to the findings of Benson *et al.* (1945), the Singapore results appear to show that the Effective Temperature Scale over-emphasizes the contribution of the wet-bulb temperature, rather than the dry-bulb temperature, to environmental stress.

The Upper Tolerable Levels of Warmth

McArdle *et al.* (1947) suggested tentatively that the thermal environmental conditions for which a four-hour sweat loss of 4·5 litres would be predicted from the P4SR nomogram represent the upper limit which fit acclimatized young men in England, carrying out work involving energy costs ranging from 54 to 200 kcal.m^{-2}.hr^{-1}, can tolerate. This was based on the observation that above this value an increasing number of their subjects failed to complete the trials. There was a measure of agreement between this conclusion and the observations made at certain levels of warmth and activity by Eichna, Ashe, Bean & Shelley (1945) and Robinson, Turrell & Gerking (1945), also derived from experiments with highly acclimatized and highly trained subjects. The paucity of convincing collapses in Series I, however, precluded a satisfactory definition on a similar basis on this occasion. The possibility was explored, therefore, of using the relation between predicted four-hour sweat losses and observed rectal temperatures and pulse rates to define the upper limiting levels of warmth. The regressions for both final rectal temperature and final standing pulse rate on P4SR were calculated from the results for the forty-eight clothing-climate combinations, for working and resting subjects separately. The mean rectal temperatures and pulse rates corresponding to P4SR values of 3·0, 3·5 and 4·0 for working subjects, and 4·0, 4·5 and 5·0 for resting subjects, were calculated from the regression equations. In addition, the upper limits of rectal temperature and pulse rate which on the average would be exceeded once in twenty times in an average subject were obtained for the same P4SR levels. These limits were termed the 'upper 5 per cent limits'. The values are shown in Table 13.

It was assumed that, provided the final rectal temperatures did not rise above 101 F and that final standing pulse rates did not exceed 140 beats/min, the majority of young naval ratings accustomed to living in the tropics would be able to complete a four-hour task entailing intermittent moderate physical exertion of the order involved in these experiments. This assumption was supported by a considerable body of evidence (and afterwards further supported by the results of subsequent experiments conducted at Singapore).

The calculated mean final rectal temperature and mean final standing pulse rate for working subjects were found to correspond approximately to 101°F and 140 beats/min when the P4SR was 3·5. On the other hand, for resting subjects the calculated mean values were still considerably below these levels even when the P4SR Index was as much as 5. It was therefore suggested that a P4SR Index of 3·5 would represent the upper tolerable levels of warmth for fit young men performing a task comparable to that of the working subjects in the experiments of Series I, provided that other conditions, such as the length of exposure and the level of environmental warmth experienced when not exposed to hot conditions, corresponded to those for the Singapore subjects. The results of Series I, however, did not provide a basis for determining the upper tolerable level for men in situations corresponding to that of the resting subjects. Environmental conditions likely to produce a final rectal temperature of 101°F and a final pulse rate of 140 beats/min for these subjects were represented by a P4SR value considerably greater than 5 and, consequently, outside the range of these experiments.

DISCUSSION AND CONCLUSIONS

The differences between the physiological reactions observed at Singapore and those predicted from the nomogram could have arisen in three ways: (a) the differential responses (e.g., the beneficial effects of wearing overalls as compared with shorts at high environmental temperatures (120°F) as opposed to their adverse influence at moderately warm conditions (90°F)) observed at Singapore might have existed in the London results but have been masked in the process of averaging which led to the construction of the nomogram; (b) they might not have occurred in London and have been due to some reaction of naturally acclimatized men at Singapore which the artificially acclimatized men in London did not share, and (c) the status of acclimatization of the men in London and in Singapore might have been the same, and real differences might have existed between the two groups in the effects of the various environmental factors.

The position was further complicated by a number of unforeseen events in Singapore, all of which tended to reduce the precision of the comparisons which could be made. There was the alteration in the original experimental plan. The division of the men into teams on the basis of their capacity to sweat and the arrangement that the heaviest sweater was always Subject No. 1 in each team and the lightest sweater Subject No. 4 was a serious error. The demonstration that there were significant differences between the initial rectal temperatures and pulse rates in the morning and the afternoon was not perhaps unexpected, but the effect was made more serious by the necessity, owing to a breakdown in the air-conditioning machinery, to hold all the trials for two environments in the morning. Perhaps the most serious complication of all was the apparent alteration in the acclimatization status of the subjects during the course of the series of experiments. It appears reasonably certain that the degree of acclimatization was higher at the end of the series of experiments than at the beginning, and it is possible that it was even higher about the middle than at the end of the series.

The authors of the report on Series I were of the opinion, therefore, that it was essential that further experiments should be conducted in Singapore with subjects acclimatized artificially to heat by a procedure similar to that of

Benson *et al.* (1945). Such experiments were to be designed to settle beyond all doubt the specific points of disagreement. Because of the wide variation from day to day in the observational data, it would be necessary to increase the number of replications of any one environmental condition.

It was considered that if the results of these experiments on men acclimatized artificially revealed divergences from the effects predicted from the nomogram similar to those revealed by Series I, the first explanation (a) of the Series I divergences (p. 26) would be correct, and the nomogram could be adjusted. If they supported the predictive accuracy of the nomogram, or differed both from the predicted effects and the effects observed in Series I, a difficult problem would be presented.

Finally, Series I suggested that naturally acclimatized naval ratings in Singapore were rather less acclimatized to the work and temperature levels investigated than were the subjects of the wartime experiments at the National Hospital in London. It followed that threshold levels of endurable warmth based on the latter experiments would, in general, probably be too high for men serving in ships in the tropics. However, most of the Singapore subjects had not been serving afloat for at least two months when the experiments began. It was considered, therefore, that further experiments should be conducted in Singapore on tropically acclimatized men living in visiting ships—where the thermal environment was more severe than it was ashore—to determine whether the conclusion concerning these levels applied to 'ship-acclimatized' men as well as to 'shore-acclimatized' men in the tropics.

SUMMARY

1. An account is given of the first series of experiments (Series I) conducted at Singapore.

2. The purpose of the series was (a) to determine the physiological effects on fit, naturally acclimatized men in the humid tropics of the several factors—temperature, humidity, air speed, rate of energy expenditure and clothing worn—which contribute to the stress of hot environments; (b) to compare these effects with those observed in similar experiments on artificially acclimatized men in London; (c) to compare the predictive accuracy of the P4SR nomogram with that of the Effective Temperature Scale, and (d) to determine the upper tolerable limits of heat stress.

3. The results showed that there was, in general, good agreement between the variations in body temperature, heart rate and sweat loss which the men in London and the men in Singapore exhibited when exposed to similar conditions.

4. The findings in Singapore supported the conclusions in London concerning the deleterious effects of very low air speeds on men working in hot humid conditions. There was also agreement that this deleterious effect was less for men who were resting than for those who were working and for those wearing shorts than for those wearing overalls, and when the wet-bulb temperature was 80°F than when it was 85°F.

5. The results verified the conclusion of Dunham *et al.* (1946) that the effect of air speed on sweat loss may be divided into two phases, but indicated on the average a rather greater increase in sweat loss in the second phase than that suggested by the London results. This increase was more accentuated when the subjects wore shorts than when they wore overalls.

6. There were, however, differences of importance between the behaviour of

the subjects in London and in Singapore. In London, men wearing overalls had a higher sweat loss than men wearing shorts over the whole range of climatic conditions examined. In Singapore, although this was true at 90°F air temperature, at 120°F the total sweat loss was in general greater for men wearing shorts at all the air speeds studied except the lowest, and this difference increased with increasing air speed. It was also found in London that raising the air speed above 200 ft./min for men wearing shorts, or above 300 ft./min for men wearing overalls, was accompanied by increased sweat losses and higher final rectal temperatures and final pulse rates. In Singapore, the increase in sweat loss occurred but the rise in final rectal temperature and pulse rate was not observed.

7. The results of Series I supported certain of the criticisms of the Effective Temperature Scale made by Benson *et al.* (1945) and Dunham *et al.* (1946) viz. that it does not emphasise sufficiently the deleterious effects of very low air speeds in hot humid conditions, and that at high air temperatures it indicates that the effect of increasing air speed is a continuous improvement in conditions, whereas the observed effect is first an improvement and then a worsening in conditions.

8. The conclusion by Benson *et al.* (1945) that the effective temperature overemphasizes the contribution to environmental stress of the dry-bulb temperature and under-emphasizes that of the wet-bulb temperature was not substantiated—the reverse appeared to be true.

9. Contrary to the findings of McArdle *et al.* (1947) it was shown that the P4SR nomogram predicted the physiological effects of hot environments more accurately than the Effective Temperature Scale only if the effects of the rate of working and clothing were ignored.

10. The results of the experiments indicated that, for the subjects used and for the conditions of the experiments, the upper tolerable levels of warmth were reached by those environments with a P4SR Index of 3·5. However, in view of the considerable differences between the conditions of these experiments and those under which men work afloat in wartime, it was considered that the upper tolerable levels of warmth to be permitted under action conditions in ships should not exceed those for which the P4SR nomogram predicted a sweat loss of 3 litres.

11. The points of difference between the findings in Singapore and in London, and the uncertainty as to the exact acclimatization status of the men used in these experiments, indicated the necessity for further experiments to be conducted at Singapore both on men naturally acclimatized and on men artificially acclimatized to hot environments.

CHAPTER 3. FURTHER EXPERIMENTS ON NATURALLY ACCLIMATIZED MEN

An account of the work of J. M. Adam, J. A. G. Collins, F. P. Ellis, J. O. Irwin, J. W. Jack, R. M. Jones and J. S. Weiner

The Experiments of Series II

THE complete examination of the results of the large number of experiments in Series I (Chapter 2) required a considerable amount of time. The special circumstances surrounding the establishment of the Tropical Research Unit at Singapore, and in particular the strictly limited tenure of the site, made it necessary that further experimental work should be carried out in the interim between the completion of the experimental work of Series I and its detailed evaluation. This work (Series II and Series III) has been described in full by Adam, Collins, Ellis, Irwin, Jack, John, Jones, Macpherson and Weiner (1955) under the title of 'Further studies on the effects of exposure to varying levels of environmental stress' and forms the subject of this and the succeeding chapter.

The preliminary examination of the results of Series I had made it plain that further information was required on two major points—the phenomena of acclimatization, and the precise, quantitative effects of variations in the several factors of climate, metabolic rate and clothing, which together determine the stress of hot environments.

The second series of experiments, Series II, was undertaken, therefore, with two main objectives. The first was to establish the acclimatization status of men serving in the tropics and to relate it on the one hand to that of the artificially acclimatized men used in the experiments in London, and on the other to the maximum degree of acclimatization that could be achieved by men living under tropical conditions.

The second objective was to re-examine the reactions of naturally acclimatized men to changes in the several factors in the thermal environment, more especially those reactions which had been found in Series I to be at variance with those reported in London. This was felt to be desirable in order to determine whether the differences between the reactions of the subjects used in Series I and those used in London could be confirmed and, furthermore, whether they were associated with a particular degree of acclimatization. It was thought that this could be done without detracting from the first and main objective of the series of experiments.

If the effect of acclimatization is to be assessed, it is necessary to examine the reactions of subjects over a wide range of conditions. If this is not done, changes may escape detection. It could be, for example, that at a moderate air temperature no difference would be detected in the responses of men in different states of acclimatization whereas at a high air temperature differences would be evident, or *vice versa*.

The experimental plan adopted for Series II was as follows. The series was divided into two parts. In the first part, naturally acclimatized men were exposed to a range of environmental conditions whilst at the same time every precaution was taken to maintain them in their naturally acclimatized state. They then underwent a period of intensive acclimatization and this was followed by a re-examination over a range of the conditions included in the first part.

It was considered that a comparison of the results of the first and second parts of the series would provide a measure of the effects of the intensive acclimatization. The results of the first part would provide further evidence about the effects of the several thermal factors on men in the naturally acclimatized state, and it would be possible to compare these findings with those of Series I.

Experience gained in Series I, however, had made it plain that in the first part of the series of experiments the level of acclimatization might change despite all efforts to the contrary. A check was required on this, and it was provided by the inclusion of a series of four uniformity trials held before and after the two parts of the main series. The results of these uniformity trials were to be used to make a further assessment of the level of acclimatization throughout the whole series of experiments and also to correct for the differences between subjects in the analysis of the first part.

METHODS

An outline of the experimental plan is given below.

Stage	
1	Pre-experimental uniformity trial (UT_1)
2	Part 1 (naturally acclimatized state)
3	Pre-acclimatization uniformity trial (UT_2)
4	Intensive acclimatization (12 days)
5	Post-acclimatization uniformity trial (UT_3)
6	Part 2 (re-test, highly acclimatized state)
7	Post-experimental uniformity trial (UT_4)

There was an initial uniformity trial which was followed immediately by the main part of the Series (Part 1). This was followed by a period of intensive acclimatization extending over 12 days, preceded and followed by uniformity trials. Then followed Part 2 of the experiment in which the subjects were considered to have reached the maximum degree of acclimatization. The series was then concluded by a fourth uniformity trial.

Twelve fit healthy young naval ratings were used as subjects. They were divided at random into three teams each of four men. Their physical characteristics are summarized below.

	Mean	*Range*
Age (yr)	24	20 – 38
Height (cm)	173·2	161·3 –185·4
Weight (kg)	66·05	52·73– 75·98
Surface area (m^2)	1·79	1·54– 1·98
Period in tropics (months)	18·6	7 – 24

These subjects resembled very closely both the men used in Series I and those used at the National Hospital, London (pp. 14 and 281).

The environmental conditions used in Part 1 (naturally acclimatized state) were divided into two sections, Section A and Section B. Section A was the test proper and consisted of all combinations of dry-bulb temperatures 90°F and 120°F, wet-bulb temperatures 83°F and 88°F, and air speeds of 20, 100, 300 and 500 ft./min. Section B was an entirely separate experiment intended to provide a measure of the effects of low air speed over a wider range of environmental conditions than in Series I. It comprised all combinations of dry-bulb temperatures 90°F and 120°F and wet-bulb temperatures of 80°F, 83°F, 85°F and 88°F at the one air speed, 20 ft./min.

During Part 1 every care was taken to see that the state of natural acclimatization was maintained. All the environments in Part 1 (Sections A and B together) were classified as moderate (those at dry-bulb 90°F) or severe (those at dry-bulb 120°F). The order of application of these two types of treatment was randomized separately, and the men were exposed only twice per week to hot room conditions, one exposure being to a moderate environment and the other to a severe one, so that exposure to severe environments occurred not more than once in 7 days.

The environmental conditions used in Part 2 (highly acclimatized state) were all combinations of dry-bulb temperatures 90°F and 120°F, wet-bulb temperatures 83°F and 88°F and air speeds of 20, 100 and 300 ft./min. The men were exposed twice weekly as before but, to ensure that they maintained their high degree of acclimatization, on those days in which they were not actively engaged in an experiment they were exercised under hot conditions in another room.

Series II. Allocation of work-clothing combinations to subjects

Dry-bulb (°F)	Wet-bulb (°F)	Air Speed (ft./min)	Work-clothing				Subject			
			Subjects				Work-clothing			
			1	2	3	4	a	b	c	d
Part 1 (pre-acclimatization test)										
Section A										
90	83	20	d	b	c	a	4	2	3	1
		100	c	d	a	b	3	4	1	2
		300	b	a	d	c	2	1	4	3
		500	a	b	c	d	1	2	3	4
90	88	20	d	a	c	b	2	4	3	1
		100	c	a	d	b	2	4	1	3
		300	b	d	a	c	3	1	4	2
		500	d	c	b	a	4	3	2	1
120	83	20	d	c	a	b	3	4	2	1
		100	b	c	a	d	3	1	2	4
		300	a	b	d	c	1	2	4	3
		500	a	c	d	b	1	4	2	3
120	88	20	c	a	b	d	2	3	1	4
		100	b	a	c	d	2	1	3	4
		300	c	d	b	a	4	3	1	2
		500	b	d	c	a	4	1	3	2
Section B										
90	80	20	a	c	b	d	1	3	2	4
90	83	20	d	b	c	a	4	2	3	1
90	85	20	a	d	b	c	1	3	4	2
90	88	20	d	a	c	b	2	4	3	1
120	80	20	c	b	d	a	4	2	1	3
120	83	20	d	c	a	b	3	4	2	1
120	85	20	d	b	a	c	3	2	4	1
120	88	20	c	a	b	d	2	3	1	4
Part 2 (post-acclimatization test)										
90	83	20	d	b	c	a	4	2	3	1
		100	c	d	a	b	3	4	1	2
		300	b	a	d	c	2	1	4	3
90	88	20	d	a	c	b	2	4	3	1
		100	c	a	d	b	2	4	1	3
		300	b	d	a	c	3	1	4	2
120	83	20	d	c	a	b	3	4	2	1
		100	b	c	a	d	3	1	2	4
		300	a	b	c	d	1	2	3	4
120	88	20	c	a	b	d	2	3	1	4
		100	b	a	c	d	2	1	3	4
		300	c	d	b	a	4	3	1	2

a — shorts working
b — shorts resting
c — overalls working
d — overalls resting

The two levels of work (the step-climbing routine and resting) and clothing (shorts and overalls worn over shorts) used in Series I were also used in this experiment.

The allocation of the work-clothing combinations ('postures') to the subjects in each team is shown on p. 31. It will be seen that this arrangement makes the separation of climate-posture interaction from subject effects difficult. Further, the treatment effects themselves are only independent of subjects if subjects do not interact with treatments. (Unfortunately, this is not so. One of the major difficulties in human climatic experiments is the great variation between individuals in the pattern of response.)

The experimental routines for both sitting and working subjects followed closely those used in Series I (p. 15). During the experiments the subjects were allowed to drink as much water as they desired, and after leaving the chamber working subjects were exhorted to drink at least 500 ml. of a 0·3 per cent solution of sodium chloride, and resting subjects at least 250 ml.

The period of intensive acclimatization was of 12 days (two working weeks) duration. The men were exposed daily to an environment of dry-bulb temperature 100°F, wet-bulb temperature 90°F, and air speed 300 ft./min. In this environment they step-climbed (on a stool 12 in. high 12 times per min) for 10 min and then rested for 20 min. The duration of the exposure was 120 min for the first two days, 180 min for the following four days and 240 min for the last six days.

The four uniformity trials were conducted in an environment of dry-bulb 90°F, wet-bulb 86°F and air speed 50 ft./min. The men wore white drill shorts and followed the routine for working subjects.

RESULTS

Changes in Acclimatization

The Results of the Uniformity Trials

The individual results in the four uniformity trials for total sweat loss and for rectal temperature and pulse rate after the third work period are set out in Table 14, and Table 15 gives the significance of the changes which occurred between successive uniformity trials and between the first and the last, and the second and the last trials.

Total sweat loss. The sweat losses in the first uniformity trial revealed large differences between individuals. The range (1420–2740 g) indicates that one subject lost nearly twice as much sweat as another. The scatter about the mean (1991 g) was very large. If these results are compared with those of the second uniformity trial (after Part 1) it will be seen that, without exception, there was an increase (which varied from 330 to 1040 g) in the amount of sweat secreted. The results did not become, as might have been expected, more uniform with training—the range is very similar to that of the first trial. This means that during the course of Part 1 of the experiment, despite all precautions to the contrary, a change occurred in the rate of sweating of the men; this change was statistically highly significant (Table 15). Such an increase in sweating is usually taken to indicate an increase in the degree of acclimatization. It is impossible to say at what rate this increase of sweating occurred, but it is most unlikely that it was uniform throughout the period.

The period of intensive acclimatization intervened between the second and third uniformity trials. A comparison of the results of these two trials shows that, on the average, there was no alteration in the amount of sweat lost. In the case of seven subjects the amount of sweat lost increased, but for the remaining five there was a decrease. Increases and decreases of more than 500 g occurred. Nor were the results more uniform—the range (1810–3285 g) is even greater than during the second trial.

Similarly, there was no significant difference between the third and fourth, or the second and fourth uniformity trials.

If the amount of sweat secreted is accepted as the sole criterion of acclimatization, these results mean that the naturally acclimatized subjects became more acclimatized during Part 1 of the experiment when every attempt was made to prevent this occurring, and that the further period of intensive exposure to heat intended to produce and maintain a higher degree of acclimatization was without effect.

Although it was not possible to demonstrate any significant change between the second and fourth uniformity trials (UT_2—UT_4 is significant only at the 10 per cent level), there does seem to be some tendency for the production of sweat to decline with time from the high value reached at the end of Part 1. (That this was a real effect received some support from the results in Series III in which it was possible to observe the changes with time over a much longer period.)

Rectal temperature. A similar comparison of the behaviour of the rectal temperature at the end of the third work period in the four uniformity trials (Tables 14 and 15) produces a conflicting picture. There was no change in the rectal temperature between the first and second uniformity trials, but between the second and third trials (the period of intensive acclimatization) there was, on the average, a significant decrease. There was no change during Part 2 of the experiment, and the rectal temperature in the final uniformity trial was significantly lower than in the first.

A comparison of the results for sweat loss and rectal temperature shows that between the first and second uniformity trials the behaviour of the subjects altered in that for the same rectal temperature they produced a greater amount of sweat; between the second and third uniformity trials their behaviour altered in that they continued to secrete an increased amount of sweat despite a fall in the rectal temperature; and between the third and fourth uniformity trials this new behaviour was maintained.

Pulse rate. The findings with respect to pulse rate after the third work period (Tables 14 and 15) provide an exact parallel to those for rectal temperature. There was no change between the first and second trials, but the period of intensive acclimatization was followed by a significant decrease of 13 beats/min, and this decrease persisted throughout the second part of the experiment.

Summary. The foregoing findings may be summarized as follows. The amount of sweat secreted in the second, compared with that secreted in the first, uniformity trial indicates that there was a considerable change in the acclimatization of the subjects during Part 1 of the series of experiments. The change in the behaviour of the rectal temperature and the pulse rate between the second and third uniformity trials indicates that the period of intensive acclimatization further changed the acclimatization status of the subjects. The values for the rectal temperature and pulse rate found in the final uniformity trial indicate that this high level of acclimatization was maintained during Part 2 of the series of experiments. It must be remarked here, and will be discussed further later, that these findings and conclusions are not entirely in agreement with the usually accepted concept that the phenomenon of acclimatization to heat is associated with an increase in the amount of sweat secreted and a decrease in the rise in rectal temperature and pulse rate on exposure to hot environmental conditions.

The Results Before and After the Period of Intensive Acclimatization

After the conclusion of Part 1 of the experiment the subjects had undergone a period of intensive acclimatization and had then been re-tested (Part 2) at all combinations of dry-bulb 90°F and 120°F, wet-bulb 83°F and 88°F, and air speeds of 20 ft./min, 100 ft./min and 300 ft./min. Each of the four work-clothing combinations at each climate combination had been allotted to the same member of the team in the re-test experiments as in the initial experiments (p. 31). It was considered that the comparison of the results of the two parts would provide a more precise measure of the effects of the intensive acclimatization than that provided by the series of uniformity trials, because of possible differences associated with the response to a particular level of heat stress or to a particular work-clothing combination.

Total sweat loss. For statistical reasons the treatment of the results for sweat loss differed somewhat from the treatment of the rectal temperature and pulse rate results. The difference between the sweat loss in Part 1 and that in Part 2 was examined separately for each of the four combinations of air temperatures 90°F and 120°F, and working and resting subjects. None of these differences was significant. The mean values of the differences, and their '*t*' values were:

	Dry-bulb 90°F		Dry-bulb 120°F	
	Working	Resting	Working	Resting
Difference (g)	74	30	−222	16
'*t*' value	1·23	0·69	1·74	0·23

The values for each of the four temperature work-rate combinations were analysed separately. The results did not give any indication that sweat losses in the re-tests of Part 2 differed systematically from those in Part 1 of the experiment.

These results can be considered to be in agreement with those of the uniformity trials which showed that the sweat-loss response in the second part of the experiment lay between that at the beginning and that at the end of the first part.

Rectal temperature. The rectal temperature after the third work period, as might be expected from the results of the uniformity trials, was on the average 0·35°F lower after the period of intensive acclimatization than before, and this difference was significant at the 1 per cent level.

The findings of the uniformity trials justified an analysis of variance of these results, and the significant mean differences are given in Table 16.

These results can best be interpreted as meaning that, in general, the more severe the conditions the greater is the effect of the process of acclimatization on the rectal temperature. The difference was greater at 120°F than at 90°F and greater for working than for resting subjects. The significant value for the interaction of air speed and work-clothing is chiefly due to the large value at 100 ft./min for men working in overalls. It is doubtful, however, whether this represents a genuine effect.

Pulse rate. The results for the pulse rate at the end of the third work period were examined in the same fashion as those for the rectal temperature. The pulse rate after intensive acclimatization was, on the average, 9·0 beats/min lower than before the intensive acclimatization, and this difference is significant at the 1 per cent level.

The differences were submitted to an analysis of variance and the appropriate mean values for significant effects are given in Table 17. The effect does not appear to vary much with climate but is greater for working subjects (mean value 11·8 beats/min) than for resting subjects (mean value 6·3 beats/min); this, to some extent, supports the finding for rectal temperature.

The Effects of the Several Environmental Factors on Naturally Acclimatized Men

Total sweat loss. The design of the experiment precluded any rigorous analysis of the results for total sweat loss. A systematic analysis of log $(1 + x)$ (where x is the sweat loss in litres corrected by the method of analysis of covariance using the results of the second uniformity trial) was performed. The transformation was necessary because the variation between the subjects depended upon the severity of the treatment. At high levels of stress the variability was much greater than at low levels of stress, i.e., the variance was proportional to the mean.

The results of this analysis provided little information of value for a number of reasons. The use of such a transformation makes it extremely difficult to interpret the meaning of the interactions. Again, it is very questionable whether it is permissible to use the results of the second or any uniformity trial as a basis for correction when the behaviour of the subjects varied so much between the first and second uniformity trials. A final complication was that some subjects failed to complete the tests in one or more of the most severe environments, and it was considered that no method of estimating missing values was entirely satisfactory.

The results of Section A and Section B were therefore summarized separately as tables of mean values (Table 18). It is not possible to make an exact comparison, although some effects—for instance, the main effects of temperature, humidity, work rate and clothing—are undoubtedly significant, but the results provide valuable material for comparison with the results of Series I, and this comparison will be made in the discussion of the results of Series III (Chapter 4).

Rectal temperature. Two values of the rectal temperatures, those recorded after the third and fourth (final) work periods, were examined. The results proved to be very similar and reference will be made here only to the results for the final rectal temperature.

The results of the uniformity trials had shown that in this case they could justifiably be used for the correction of differences between subjects by analysis of covariance. The subsequent analysis of variance showed that all the main effects, and most of the first order interactions, were significant. Few of the second order interactions were significant and the meaning of those that were significant was difficult to interpret.

In order to facilitate discussion later, rather than the usual tables of significant mean values a table of the mean values for all treatment combinations is given (Table 19).

Allowing for the absence of an effect due to changes in air speed in Section B, the results in Sections A and B are very similar. The general finding that the effect of increasing the level of one factor depends upon the level of the remaining factors is quite clear. Increasing the air temperature increases the rectal temperature, as also does increasing the humidity, but the effect of increasing the air temperature is much greater at the higher level of humidity. Similarly the effect of increasing the metabolic rate is increased by raising the air temperature, increasing the humidity or increasing the amount of clothing worn.

The effect of increasing the air speed is much more complex; conditions may be either improved or worsened depending upon the levels of temperature and humidity and on the amount of clothing worn. The detailed discussion of this most important effect can best be postponed until the corresponding results of Series III are examined.

Pulse rate. The results for the pulse rate were examined in the same manner as those for rectal temperature; in this case the pulse rate after the third work period has been chosen for presentation. The mean values for all treatment combinations after this work period are set out in Table 20.

The results of Section A show plainly that, on the average, increasing the air temperature, the humidity, the rate of working or the amount of clothing worn increased the pulse rate. The effect of increasing the air speed was much more complicated. Examination of Table 20 will show that it varied not only with each combination of air temperature and humidity (e.g., at dry-bulb 90°F, wet-bulb 88°F, increasing the air speed produced on the average a decrease in the pulse rate; at dry-bulb 120°F, wet-bulb 83°F it produced an increase) but with each work-clothing combination as well. For this reason the detailed discussion of the effects, as in the case of the rectal temperature, will be postponed until the results of Series III are discussed.

Section B provides a much more comprehensible picture. The effect of increasing the air temperature is plainly to increase the pulse rate and the steady increase in pulse rate with increasing wet-bulb temperature is also plain. Increasing the rate of working or the amount of clothing worn likewise increases the pulse rate.

DISCUSSION AND CONCLUSIONS

A comparison of the results of the first and second uniformity trials in Series II provided very strong evidence that, despite every care, the attempt to maintain the subjects in the state of ‘natural acclimatization’ to tropical conditions had not been successful. The change in the rate of sweating which had occurred meant that an attempt to ‘correct’ the P4SR scale on the basis of the results of Series II for the apparent anomalies found in Series I would rest on uncertain ground.

In fact, the results of Series II gave strong support to the conclusion from Series I that the effects of the various thermal factors ‘should be re-examined with subjects who, from the outset, are as nearly as possible in the maximum state of acclimatization and training for the work which they have to carry out’. It was presumed that this state was the one most likely to be maintained uniformly throughout a series of experiments.

The next series of experiments (Series III), to be described in the following chapter, was therefore designed to examine the effects of the various thermal factors on men who were artificially highly acclimatized and who, therefore, might be expected to exhibit a constancy of behaviour. For this reason the results of Series II and, especially, the comparisons that can be made with the results of the London experiments and the Series I experiments will be discussed in detail in the next chapter in conjunction with the results of Series III.

The problem of the behaviour of naturally acclimatized men and the associated problem of the status of acclimatization of men serving in Singapore could not be regarded as satisfactorily settled but it was clear that the approach would have to be along other lines than those employed in Series I and Series II. A series of experiments (Series IV) designed to this end will be described in Chapter 5.

The observations concerning the relation of sweat loss and rectal temperature in the uniformity trials (p. 33)—that an increase in sweat loss is not necessarily accompanied by a fall in rectal temperature and that a fall in rectal temperature can occur without an increased loss of sweat—are of considerable interest and may conveniently be referred to at this point. Such findings raise very interesting questions as to the partitioning of the heat exchange of the subjects which cannot be answered as there is no information as to the behaviour of their skin temperature. It is interesting to speculate why the increased sweat production in the second uniformity trial was not accompanied by a fall in the rectal temperature. There are a number of possible explanations. It could be, of course, that the sweat secreted at the second trial exceeded the maximum evaporative capacity of the environment and so ran to waste; or it could be that at the second trial there was an increase in the amount of heat produced. The latter appears unlikely, though a converse explanation might be possible for the changes between the second and third uniformity trials, viz., that with training the work was done more efficiently and the amount of heat produced diminished so that, for the same amount of sweat evaporated, the body temperature was lower. These suggestions are, of course, wholly speculative and serve merely to point to the necessity for further and more exact experiments which should include measurement of the skin temperature.

SUMMARY

1. A preliminary examination of the results of Series I (Chapter 2) indicated that further information was required on two major points: the phenomena of acclimatization and the precise physiological effects of the several factors contributing to the stress of hot environments.

2. A second series of experiments (Series II) was therefore performed with the purpose of (a) comparing the acclimatization status of men serving in the tropics with that of men artificially acclimatized to heat and (b) re-examining the reactions of naturally acclimatized men to changes in the thermal environment, especially those reactions which in Series I had been found to be at variance with those observed in London.

3. In this series, the subjects were exposed to a range of environmental conditions and their reactions observed, every care being taken not to acclimatize them further (Part 1). They were then submitted to a period of intensive acclimatization, after which their reactions were again examined over the range of conditions previously used (Part 2).

4. Uniformity trials were performed at the beginning of the series, at the conclusion of Part 1, after the period of intensive acclimatization and at the conclusion of Part 2.

5. The results of these uniformity trials showed that the mean sweat loss increased during Part 1, was unaffected by the period of intensive acclimatization and was unchanged during Part 2. The final rectal temperature and the final heart rate were unchanged by the first part of the series, decreased after the period of intensive acclimatization and thereafter remained unchanged.

6. These findings, although conflicting, suggested that the attempt to maintain the subjects in their natural state of acclimatization during the first part had not been entirely successful. It should be noted that the increase in the rate of sweating during Part 1 was not accompanied by a fall in rectal temperature.

7. Comparison of the findings in Part 1 and Part 2 showed that there was no significant difference between the sweat losses of the two groups of experiments. The rectal temperature after the third work period was, however, less in Part 2 than in Part 1 and, in general, the more severe the conditions, the greater the difference between the rectal temperature before and after the intensive acclimatization. The heart rate after the third work period was less after acclimatization than before, and although the effect did not differ greatly with the air temperature, humidity or air speed, the decrease was greater for working than for resting men. These results are in general agreement with those of the uniformity trials.

8. The analysis of the responses of the subjects before and after the intensive acclimatization to changes in the several factors in the environment was made difficult by a defect in the experimental plan. These responses are discussed in detail, in conjunction with the results of Series III, in Chapter 4. In general they support, especially with respect to the effects of changes in air speed, the findings in Series I.

9. The general conclusions were: (1) that, despite the precautions taken, the performance of Part 1 had not been without effect on the acclimatization of the subjects and that some other method would have to be devised to determine the acclimatization status of men serving in the tropics; (2) that, owing to the changing state of the subjects, any attempt to correct the P4SR nomogram on the basis of these experiments would rest on uncertain ground, and (3) that it was important, therefore, to examine the reactions of subjects in a stable state of acclimatization (i.e., artificially maximally acclimatized) if a critical assessment of the findings at London and the P4SR nomogram was to be made.

CHAPTER 4. THE EFFECTS OF ENVIRONMENTAL STRESS: MEASUREMENTS ON ARTIFICIALLY ACCLIMATIZED MEN

An account of the work of J. M. Adam, F. P. Ellis, J. O. Irwin, J. W. Jack, R. T. John, R. M. Jones, R. K. Macpherson and J. S. Weiner

The Experiments of Series III

THE chief object of the third series of experiments (Series III) performed at Singapore (Adam *et al.* 1955) was to make an accurate quantitative assessment, in terms of sweat loss and elevation of pulse rate and deep body temperature, of the effects of the several factors comprising the thermal environment (air temperature, humidity and air speed) on maximally acclimatized men working at two levels of energy expenditure and wearing two types of clothing.

Series III was intended to cover more ground than Series II. Series II had dealt with two levels of air temperature, 90°F and 120°F, which were then regarded as the extreme limits of the range of thermal conditions of interest to the Royal Navy. It is not justifiable, however, to assume that the response to hot conditions is linear between these two extremes, so a third air temperature, 100°F, was included in the range of conditions examined.

A second object of Series III arose from the fact that in Series I and Series II the need to share the facilities at the Tropical Research Unit with the group working on applied psychology had made it necessary to perform physiological experiments in the morning and in the afternoon on alternate days. The results of these two series of experiments had suggested that the responses of subjects treated in the mornings differed from those of subjects treated in the afternoons. In view of the known existence of physiological rhythms, e.g. in body temperature, it was felt that this matter should be further explored in Series III. For this reason each treatment combination was applied twice—in the morning and in the afternoon.

A third object of this series was to compare its findings on the effects of changes in the levels of the environmental factors with the corresponding findings in London.

METHODS

This series essentially comprised two distinct experiments. Section A consisted of all combinations of two levels of air temperature (90°F and 120°F), two levels of wet-bulb temperature (85°F and 88°F), four levels of air speed (20, 100, 300 and 500 ft./min), two levels of energy expenditure (working and resting), and two levels of clothing (shorts and overalls). Section B consisted of all combinations of one air temperature (100°F), two levels of wet-bulb temperature (80°F and 83°F), and the same levels of air speed, energy expenditure and clothing as in Section A.

The allocation of the subjects to the several work-clothing combinations is given on the following page. The experimental procedure followed closely that of Series II (Chapter 3) from which it differed only in the most minor details. It should be particularly noted however that the subjects were allowed to drink unsalted water *ad libitum* during the experiments.

Series III. Allocation of subjects to work-clothing combinations

Wet-bulb (°F)	Air Speed (ft. min)	Dry-bulb 90° F					Dry-bulb 100° F					Dry-bulb 120° F				
		Work-clothing					Work-clothing					Work-clothing				
			a	b	c	d		a	b	c	d		a	b	c	d
80	20						am	1	2	4	3					
							pm	3	4	2	1					
	100						am	1	2	4	3					
							pm	3	4	2	1					
	300						am	1	2	3	4					
							pm	3	4	2	1					
	500						am	1	2	3	4					
							pm	3	4	2	1					
83	20						am	2	3	1	4					
							pm	4	1	3	2					
	100						am	2	3	1	4					
							pm	4	1	3	2					
	300						am	2	3	1	4					
							pm	4	1	3	2					
	500						am	2	3	1	4					
							pm	4	1	3	2					
85	20	am	1	2	4	3						pm	2	3	1	4
		pm	3	4	2	1						am	4	1	3	2
	100	pm	1	2	4	3						am	2	3	1	4
		am	3	4	2	1						pm	4	1	3	2
	300	am	1	2	4	3						pm	2	3	1	4
		pm	3	4	2	1						am	4	1	3	2
	500	pm	1	2	4	3						am	2	3	1	4
		am	3	4	2	1						pm	4	1	3	2
88	20	pm	2	3	1	4						am	1	2	4	3
		am	4	1	3	2						pm	3	4	2	1
	100	am	2	3	1	4						pm	1	2	4	3
		pm	4	1	3	2						am	3	4	2	1
	300	pm	2	3	1	4						am	1	2	4	3
		am	4	1	3	2						pm	3	4	2	1
	500	am	2	3	1	4						pm	1	2	4	3
		pm	4	1	3	2						am	3	4	2	1

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting

am = morning
pm = afternoon

1, 2, 3 and 4 = the four subjects of each team

The subjects—twelve healthy young sailors—had the following characteristics:

	Mean	*Range*
Age (yr)	20	18 – 24
Height (cm)	172·4	160·7 – 182·9
Weight (kg)	61·87	53·36 – 77·50
Surface area (m^2)	1·73	1·57 – 1·93
Period in tropics (months)	17·4	9 – 28

They were divided into three teams, each of four men, and the numbers 1 to 4 were allocated to the members of each team by lot.

The subjects were acclimatized by a graded programme of step-climbing at a dry-bulb temperature of 100°F, a wet-bulb temperature of 94°F and an air speed of 50 ft./min for 14 successive days and then the experiment proper was begun. Uniformity trials were performed before and after the period of acclimatization, and at intervals of 4 weeks throughout the whole series of experiments—the last following immediately on the conclusion of the series. The experimental procedure in the uniformity trials was exactly that in the experiment proper for working subjects, except that all the men wore shorts, and arm sweat was collected in sweat bags for the first 160 min. The environment used was dry-bulb 90°F, wet-bulb 86°F, air speed 50 ft./min. These trials and their results will be described in Chapter 10.

RESULTS

As the chief aim of Series III was the exact quantitative evaluation of the effects of the several factors which constitute the thermal environment, the statistical analysis of the results is given in full in Tables 21–32. The main findings only are described in this section.

The systematic analysis was carried out for Section A and Section B separately. The variates chosen for examination in detail were: the four-hour (total) sweat loss; the rectal temperature at the end of the third, at the beginning of the fourth and at the end of the fourth (final) work period; and the standing pulse rate at the corresponding times.

Total (Four-hour) Sweat Loss

All the main effects of climate and work rate and clothing, except the average air-speed effect in Section B, were highly significant. The effects of air temperature and humidity and their interaction all varied with air speed. The effect of clothing and of rate of work also varied with the air speed. The effect of humidity varied a little with the work rate and, in Section A, with the amount of clothing worn. The effect of air temperature did not vary, on the average, with the amount of clothing or the rate of working, but the interaction of these two last factors with air temperature varied with air speed. The average morning-afternoon effect was not significant, but the effects of air temperature and work rate appeared to be slightly greater in the morning in Section A, while in Section B the effect of humidity appeared to be slightly greater in the afternoon. These are the general conclusions; the results will now be examined in greater detail.

Section A. In the first part of Table 21 is set out the interaction between the effect of air temperature and air speed. It will be seen that, on the average and at each air speed separately, there was a much smaller sweat loss at the lower dry-bulb temperature (90°F) than at the higher (120°F), but that the exact effect of the air speed varied with the air temperature. At 90°F, increasing the air speed resulted in a decrease in the amount of sweat secreted and the change was particularly great between 20 and 100 ft./min. At 120°F, on the other hand, although increasing the air speed from 20 to 100 ft./min produced a fall in the amount of sweat secreted, increasing the air speed further from 100 ft./min to 300 ft./min produced little change, and increasing the air speed still further to 500 ft./min produced an increase in the amount of sweat secreted.

The inter-relationship of air speed and humidity is also set out in Table 21. The sweat loss was greater at the higher humidity but as the air speed increased the effect of increasing the humidity decreased.

The combined inter-relationship of air temperature, humidity and air speed is set out in detail in the same table. It may be summarized as follows. The average effect of increasing the air speed was a fall in sweat rate followed by a rise as the speed was further increased. This was true also at 120°F, but at 90°F the fall persisted at the higher speeds. The effect of increasing the wet-bulb was greatest at the lowest air speed and diminished as the air speed rose. The effect of increasing the humidity was greater at the higher dry-bulb (120°F) than at the lower (90°F).

Perhaps the clearest appreciation of the effect of increasing the air speed can be obtained by considering each of the four dry- and wet-bulb combinations separately. At dry-bulb 90°F, wet-bulb 85°F, increasing the air speed resulted in a continuous fall in the amount of sweat produced. When the humidity was increased (dry-bulb 90°F, wet-bulb 88°F) the nature of the response was the same but the magnitude of the effect was greater, so that the difference between the higher and the lower humidity tended to disappear. At dry-bulb 120°F, wet-bulb 85°F, which is a 'hot-dry' condition, increasing the air speed at first produced a small fall but this was followed at a relatively low air speed by a marked rise. When, however, the moisture content of the air was increased, increasing the air speed produced at first a very marked fall which diminished with the rise in air speed, although it was not until the air speed reached between 300 and 500 ft./min that this diminished fall gave place to a rise in the amount of sweat produced.

The second part of Table 21 shows very clearly that the effect of increasing the amount of clothing worn was greater for working than for resting men. In other words, the effect of increasing the energy output depends on the type of clothing worn and will be greater for men wearing overalls than for men wearing shorts.

The result of the interplay of all the factors involved in climate and work and clothing is extremely complex; the relationships are set out in full in the third part of Table 21 and the main findings may be summarized as follows. The effect of increasing the humidity was greater for working than for resting subjects and greater when overalls were worn than when shorts were worn. The effect of increasing the work rate was greater at the lower air speeds, except for the anomalous case when overalls were worn at dry-bulb 120°F and air speed 20 ft./min.

The inter-relationship of clothing and air speed is particularly complex. In general the effect of clothing diminished with rising air speed. The fact that this effect was less than would be expected for men working in 'still' (20 ft./min) air at dry-bulb 120°F strongly suggests that under these conditions the sweat rate for those working in overalls was approaching its maximum value.

In the case of subjects resting at dry-bulb 120°F, when the air speed was 500 ft./min men in shorts had a higher average rate of sweating than men in overalls. This phenomenon of the alteration in the relative effects of overalls and shorts is usually referred to as 'crossing over' and is illustrated in detail in Table 22. The statistical analysis shows that this effect was significant only for resting subjects at dry-bulb 120°F. The transition point was at about 100 ft./min at wet-bulb 85°F but higher at wet-bulb 88°F.

Section B. The mean values for the significant effects in Section B are set out in Table 23. At wet-bulb 83°F there was a fall in the amount of sweat produced as the air speed increased from 20 to 100 ft./min, followed by a rise as the air speed was further increased, but at wet-bulb 80°F there was no clear trend with air speed. The average effect of clothing was significant for working but not for resting subjects. The effect of humidity was greater for working than for resting subjects and greater for overalls than for shorts.

The 'crossing over' of the clothing effect took place with resting subjects at about 100 ft./min. With working subjects there was no significant crossing over, but at wet-bulb 80°F and air speed 500 ft./min the sweat losses of men in shorts and of those in overalls were about equal (Table 24).

Sweat Loss per Square Metre of Body Surface

As the amount of sweat secreted is a function of body size, the amount of sweat lost by each man was expressed per unit of surface area and the results were analysed. The conclusions were the same as those which have just been given for total sweat loss.

Rectal Temperature after the Third Work Period

Section A. The mean values for the significant main effects and interactions are set out in Table 25. The rectal temperature after the third work period was always greater at the higher dry-bulb temperature than at the lower, and it was also higher at the higher wet-bulb temperature than at the lower. Moreover, the effect of increasing the dry-bulb temperature was greater at the higher wet-bulb temperature than at the lower. On the average, there was a steady fall with increasing air speed and this fall was particularly great between 20 ft./min and 100 ft./min, especially at the higher wet-bulb temperatures.

The effect of increasing the wet-bulb temperature also depended upon the work-clothing combinations. This effect was much greater for 'overalls working' than for the remaining combinations of work and clothing, among which the effect differed little. The difference between wearing shorts and wearing overalls was greater for working than for resting men.

The interaction between air temperature, air speed, rate of work and amount of clothing worn is particularly complicated and is set out in full in Table 25. For men working in shorts at 90°F, increasing the air speed resulted in a fall in the rectal temperature. This was also true for men wearing overalls under the same conditions—between 20 and 100 ft./min the fall was considerable. Men working in shorts at 120°F showed a fall in rectal temperature as the air speed rose from 20 ft./min to 100 ft./min, but thereafter there was no change. On the other hand, men wearing overalls under these conditions showed a fall in rectal temperature up to an air speed of 500 ft./min. For men resting at dry-bulb 90°F there was a fall as the air speed rose from 20 ft./min to 100 ft./min but thereafter increasing the air speed was apparently without effect. This was true when either overalls or shorts were worn. For men resting at dry-bulb 120°F, increasing the air speed was apparently without effect on the rectal temperature of men wearing shorts; in men wearing overalls increasing the air speed from 20 ft./min to 100 ft./min produced a fall in rectal temperature but a further increase in air speed was apparently without effect.

For men wearing shorts an increase in the wet-bulb temperature from 85°F to 88°F produced much the same effect whether they were working or resting. For men wearing overalls, however, the same increase in wet-bulb temperature produced a much larger change when they were at work than when they were at rest. The increase when they were at rest was very similar to the increase for men wearing shorts. These effects did not vary with air speed.

Section B. Of the direct effects of both climate and work-clothing combinations, only the rate of working produced a significant change in the rectal temperature (Table 26). The mean value for the rectal temperature for working subjects was 100·21 (± 0·028)°F and for resting subjects 99·13(±0·028)°F—a difference of 1·08°F. The mean difference between working and resting subjects in Section A was 1·42°F, but comparison between Section A and Section B was not possible as not only did the dry-bulb temperatures differ in the two sections but the wet-bulb temperatures also.

Probably the most valid comparison that can be made to illustrate the effects on the rectal temperature of the rate of working at different levels of environmental stress is the comparison between the increase in rectal temperature with work in Section B and the increase at dry-bulb 120°F in Section A. It so happens that the water vapour pressures in these two cases are roughly comparable. (At dry-bulb 120°F the wet-bulb temperatures of 85°F and 88°F correspond to water vapour pressures of 21·2 mm Hg and 25 mm Hg respectively, whereas at dry-bulb 100°F the wet-bulb temperatures of 80°F and 83°F are respectively equivalent to 20·7 mm Hg and 25·5 mm Hg.) The mean value for the difference between the rectal temperatures of men working and resting at dry-bulb 120°F was 1·66°F. This is considerably higher than the value at dry-bulb 100°F (Section B), viz., 1·08°F.

Rectal Temperature after the Fourth Work Period

Section A. The mean values for the significant effects for rectal temperature after the fourth (final) work period are set out in Table 27. Increasing the dry-bulb temperature or the wet-bulb temperature increased the final rectal temperature, but the effect of increasing the air temperature was greater at the higher level of humidity, especially at the lowest air speed. The rectal temperature fell sharply as the air speed increased from 20 ft./min to 100 ft./min, but when averaged over the four work-clothing combinations the fall accompanying further increase in the air speed was small, except perhaps at dry-bulb 90°F, wet-bulb 88°F. For subjects working in overalls, however, the fall persisted to 300 ft./min or 500 ft./min, irrespective of the dry-bulb temperature, while for other work-clothing combinations at dry-bulb 120°F the rectal temperature tended to rise slightly as the air speed was increased beyond 100 ft./min.

The effect of increasing the wet-bulb temperature was greater for working than for resting subjects, and for working subjects it was greater when they wore overalls than when they wore shorts.

Section B. In this section the only significant effect for the rectal temperature after the fourth (final) work period was the rate of work (Table 28). The mean value of the rectal temperature for working men was 99·95 (±0·037)°F and for resting men it was 99·16(±0·037)°F, a difference of 0·79°F.

Pulse Rate after the Third Work Period

Section A. The mean values of significant effects are set out in Table 29. Increasing the air temperature from 90°F to 120°F resulted, on the average, in an increase from 96 to 124 beats/min. Increasing the wet-bulb temperature from 85°F to 88°F resulted in an increase from 105 to 114 beats/min. At the lowest air speed, however, the effect of increasing the wet-bulb temperature at dry-bulb 120°F was much greater than at dry-bulb 90°F but this effect was not seen at the higher air speeds. The pulse rate fell as the air speed was increased from 20 ft./min to 100 ft./min but thereafter showed little change.

Increasing the rate of work always increased the pulse rate. The effect with work was greater for men wearing overalls than for men wearing shorts (on the average 40 beats/min compared with 29 beats/min), and this effect did not vary systematically with the climate—the wet- and dry-bulb temperatures and the air speed.

Increasing the amount of clothing worn usually increased the pulse rate but, as will be seen later, there were important exceptions.

Both changes in the air temperature and changes in the humidity had greater effects on working than on resting subjects. The fall in pulse rate which occurred as the air speed was increased from 20 to 100 ft./min was much greater for working than for resting subjects.

Clothing had an important effect on the changes resulting from alterations in the environment. At dry-bulb 120°F, subjects in shorts showed an increase in pulse rate as the air speed rose above 100 ft./min. This did not occur with subjects in overalls, for whom the fall persisted up to 300 ft./min. At 500 ft./min, men in shorts had a slightly higher pulse rate than men in overalls but the difference was not significant.

In summary, increasing the air speed above 100 ft./min was without effect on the average, but in the case of men wearing overalls a fall in pulse rate occurred up to an air speed of 300 ft./min. This did not occur with men wearing shorts.

Section B. In this section, at dry-bulb 100°F the pulse rate was higher on the average at the higher wet-bulb, 83°F (Table 30). This was true at the lowest air speed, but at the highest air speed the lower wet-bulb, 80°F, apparently was associated with the higher pulse rate. The results, however, were irregular and definite conclusions could not be drawn.

The pulse rate was higher for working than for resting men and the difference was greater for men wearing overalls than for men wearing shorts. For resting subjects, the difference between wearing shorts and wearing overalls was not significant.

Pulse Rate after the Fourth Work Period

Section A. The results are set out in Table 31. An increase in either the dry-bulb temperature or the wet-bulb temperature was associated with an increase in the pulse rate, but the increase with increasing dry-bulb was greater at the higher wet-bulb than at the lower.

The average effect of increasing the air speed was to reduce the pulse rate. The fall in pulse rate as the air speed rose from 20 ft./min to 100 ft./min was very marked but the fall as it rose from 100 ft./min to 300 ft./min was small, and there was no change between 300 ft./min and 500 ft./min. At dry-bulb 90°F, increasing the air speed from 20 ft./min to 100 ft./min produced a marked fall in pulse rate, and thereafter up to 500 ft./min there was a small but reasonably constant fall. At dry-bulb 120°F, the sharp fall in pulse rate between 20 ft./min and 100 ft./min was succeeded by a small fall between 100 ft./min and 300 ft./min, but between 300 ft./min and 500 ft./min there was a rise in the pulse rate so that the value at 500 ft./min was the same as that at 100 ft./min.

The pulse rate increased with increasing metabolic rate and was greater for men wearing overalls than for men wearing shorts. Increasing the amount of clothing worn produced a greater effect in working than in resting men.

The effect of variations in air speed varied with the dry-bulb temperature and the amount of clothing worn. Increasing the air speed from 20 ft./min to 100 ft./min reduced the pulse rate for both men in shorts and men in overalls at both air temperatures. At 90°F, increasing the air speed further produced a further slight fall in pulse rates. At 120°F, increasing the air speed from 100 ft./min to 300 ft./min was without effect on men wearing shorts. A further increase to 500 ft./min produced a sharp rise in the pulse rate. For men wearing overalls, increasing the air speed up to 300 ft./min conferred a further benefit but an increase from 300 ft./min to 500 ft./min was without effect. The net result was that at 500 ft./min the pulse rate of men wearing shorts did not differ from that of men wearing overalls.

The comparison of the effects on working and on resting men of increasing the air speed showed that an increase up to 300 ft./min was advantageous for working men, but that increasing it beyond 100 ft./min conferred no advantage on resting men.

Section B. The only effects on the pulse rate which were clearly significant were those of work rate and, for working subjects, the amount of clothing worn (Table 32).

Discussion

Observed Sweat Loss and the P4SR

It will be remembered that the chief purpose of Series II was to relate the acclimatization status of men serving in ships in the tropics to that of the highly acclimatized subjects used in the experiments of McArdle and his associates in London. Likewise, one of the chief purposes of Series III was to compare the findings on the effects of different levels of the environmental factors on men living in the tropics who had been further acclimatized artificially with the findings obtained in London. In each case the end may be served by comparing the observed sweat losses in the Singapore experiments with the values predicted by the P4SR nomogram.

If the sweat losses of any group of men at Singapore were compared with the P4SR values for the same environments and it was found that there was no important difference between the observed sweat losses and the corresponding P4SR values, it could reasonably be concluded that the behaviour of the men in Singapore was identical with that of the men in London. As a corollary, it could be concluded that the P4SR Index accurately predicted the amount of sweat loss for these environments, and that the state of acclimatization of the two groups was identical. It would be unlikely that the effects of acclimatization by chance accurately corrected for any errors of prediction in the P4SR.

If, however, such a comparison was made and—as is much more likely—differences were found to exist, the interpretation of such differences would depend largely upon their nature. If, for example, it was found that a difference existed for all combinations of the treatment factors and this difference was consistent in sign, and of appropriate magnitude, it would be reasonable to assume that this represented a difference between the subjects in London and in Singapore. It might be considered probable that such a constant difference indicated a difference in the acclimatization status of the two groups but the possibility that it was due to some other factor, such as age or body size, could not be excluded. It would be unlikely that the difference would be due to some constant error in the nomogram.

If, on the other hand, a difference was found to exist for some treatment combinations but not for others, or if the difference varied from treatment to treatment, the position would be less simple. The possibility that such differences might be due to differences in acclimatization status could not be excluded. It is likely that differences in the level of acclimatization would become patent only at the higher levels of stress, and that at the lower levels of stress no differences in the behaviour might be manifest. It could be, on the other hand, that these differences had nothing to do with acclimatization but merely indicated that different groups of men when treated alike react differently—a fact of the greatest importance in the interpretation of climatic experiments. Another possible explanation of such differences would be that the P4SR nomogram was in error in those values of the index which differed from the observed results for the relevant treatment combinations. This would be made more likely if such differences were found to occur with more than one group of men, and especially so if these groups possessed differing degrees of acclimatization.

It is proposed, therefore, to examine the observed sweat losses in Series II and III and to compare them with the values predicted by the P4SR nomogram, postponing for the time being the discussion of the difficulty introduced if the P4SR is considered to be a measure of environmental stress represented by a conventionalized sweat loss and not, as originally defined, the actual 'amount of sweat lost by fit acclimatized young men when exposed to the given conditions for a period of four hours'.

Energy Costs of Resting and Step-climbing

Before proceeding to compare the observed and predicted values in Series I, II and III, attention must be drawn to a difficulty which arises in the use of the P4SR nomogram. The calculation of the P4SR for men whose rate of working is greater than that of men seated at rest in chairs involves a term whose magnitude depends upon the metabolic cost of the work. It is determined in part by a secondary nomogram which determines the amount by which the wet-bulb temperature must be modified, and in part by adding a given quantity to the B4SR value obtained from the nomogram (p. 298).

In the experiments at Singapore two levels of energy expenditure were used. These were sitting at rest in chairs and following a routine of alternate periods of sitting and step-climbing which had been devised and extensively used at the National Hospital in London.

The London workers stated that the energy expenditure of sitting was 54 kcal.m^{-2}.hr^{-1}, and of step-climbing 180 kcal.m^{-2}.hr^{-1}, so that over the four-hour period of the experiment the rate of energy expenditure for the resting men was 54 kcal.m^{-2}.hr^{-1} and for the working men 111 kcal.m^{-2}.hr^{-1} (Dunham *et al.* 1946). These workers do not state how many determinations were made or the ranges or standard errors of the mean values quoted. It has been assumed that the measurements on which these values were based were made at room temperature in London.

Adam and Cague (1952) determined the energy expenditure of resting and step-climbing at room temperature in Singapore. These values were 46·8 ± 3·5 kcal.m^{-2}.hr^{-1} for sitting at rest and 164·0 ± 7·0 kcal.m^{-2}.hr^{-1} for step-climbing. These values give the average rate of energy expenditure over the four-hour period of the Queen Square routine of 47 kcal.m^{-2}.hr^{-1} for resting men and 101 kcal.m^{-2}.hr^{-1} for working men. It is not possible to say with certainty whether the values are significantly different from those obtained in London.

If the values obtained in Singapore are used in the nomogram, a distinctly smaller value is obtained for the P4SR for the working men, but not for the resting men, than would be the case if the values obtained in London were used. It was considered when the report on Series I was written by Adam *et al.* (1952) that the correct procedure for calculating the P4SR Index for men in Singapore was to use the value for energy expenditure found at Singapore. Further consideration has cast doubts on the correctness of this procedure. It would seem to imply that the energy cost of a given activity is less in Singapore than in London, because of the differences between the two environments. This may be so, but there is no certain evidence to substantiate it. If a difference does exist in the energy expenditure on a given task at room temperature in London and at Singapore, it does not necessarily follow that a similar difference exists when the same task is performed in a climatic chamber under exactly the same environmental conditions in the two geographically separated places.

There are other reasons, too, which seem to indicate that the more correct procedure is to consider that the energy expenditures during resting and working in Singapore are those determined in London—54 kcal.m^{-2}.hr^{-1} and 111 kcal.m^{-2}.hr^{-1}—rather than any other values, but it will suffice to mention only two related ones. The final stage in the calculation of the P4SR for men working in shorts requires substituting the appropriate value for M in the equation

$$\text{P4SR} = \text{B4SR} + 0{\cdot}014(M - 54)$$

where M is the metabolic cost of the work in kcal.m^{-2}.hr^{-1}. The value 54 clearly refers to the accepted value for sitting, so that if another value is chosen for M for step-climbing then another value should be inserted in place of 54. Again, the values 54 kcal. m^{-2}.hr^{-1} and 111 kcal.m^{-2}.hr^{-1} are the values assigned to the two levels of activity, sitting at rest and alternate resting and step-climbing, in the P4SR nomogram and, even if it could be shown that these values were in error, the substitution of the correct values would serve only to produce incorrect predictions from the nomogram. In the case of resting men, whatever value is chosen as the metabolic cost of sitting at rest, the nomogram will predict the same value for the P4SR because the metabolic cost of the activity only enters into the calculation if it exceeds 54 kcal.m^{-2}.hr^{-1}.

In Series II and III therefore, and in the discussion which follows, the P4SR values used are those obtained by assuming that the metabolic costs of the two levels of activity are those quoted by McArdle *et al.* (1947). This will serve to explain the discrepancies between some values quoted for Series I in this chapter and those reported by Adam *et al.* (1952) and consequently quoted in Chapter 2.

Comparison of the Observed and Predicted Sweat Losses

The regression equations relating sweat loss (y) and the P4SR value of the environment (x) have been calculated for Series II and Series III. They were found to be as follows.

Series II Part I (pre-acclimatization)

$$Y = 2{\cdot}616 + 1{\cdot}0630(x - 2{\cdot}284) \qquad (1)$$

Series II Part 2 (post-acclimatization)

$$Y = 2{\cdot}689 + 1{\cdot}1440(x - 2{\cdot}326) \qquad (2)$$

Series III Section A

$$Y = 2{\cdot}309 + 0{\cdot}9411(x - 2{\cdot}375) \qquad (3)$$

Series III Section B

$$Y = 1{\cdot}529 + 0{\cdot}8196(x - 1{\cdot}565) \qquad (4)$$

Series III Sections A and B together

$$Y = 2{\cdot}049 + 0{\cdot}9342(x - 2{\cdot}105) \qquad (5)$$

The results for Series II Part 1, Series II Part 2 and Series III (A and B) are illustrated in Fig. 1, 2 and 3. In these figures the mean values for each climate-work-clothing combination are plotted separately.

The lines drawn in Fig. 1, 2 and 3 do not represent the appropriate regression equations but the lines of ideal correspondence for which the observed sweat loss (y) would equal the P4SR Index (x). The reason for this is to emphasise the manner and extent of the divergence of the observed sweat loss from the P4SR Index.

In the discussion which follows only equations (1), (2) and (5) above will be considered. It is justifiable to treat Parts A and B of Series III together and it will simplify the discussion.

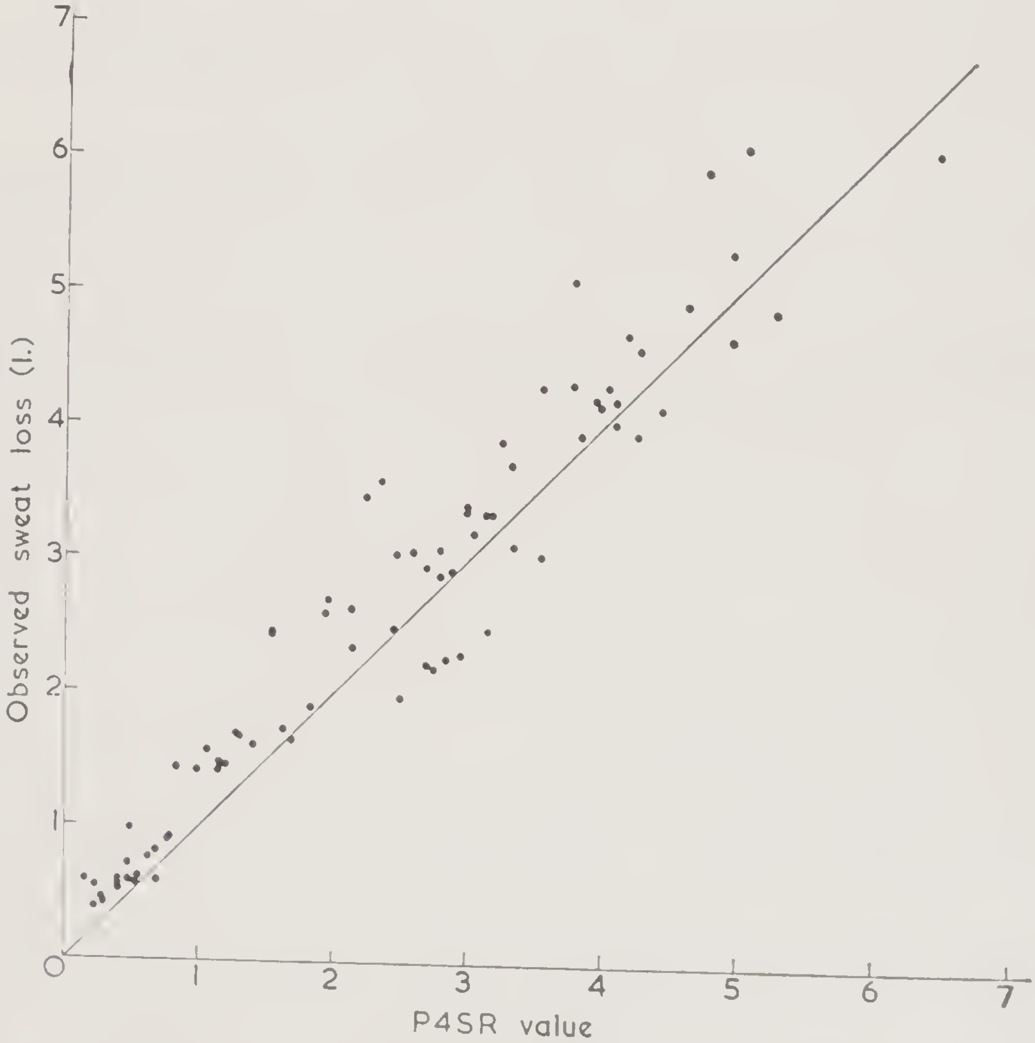

FIG. 1. Series II, Part I (pre-acclimatization). Relation between observed sweat loss and calculated P4SR Index for all climate-work-clothing combinations. The line represents ideal (1:1) correspondence.

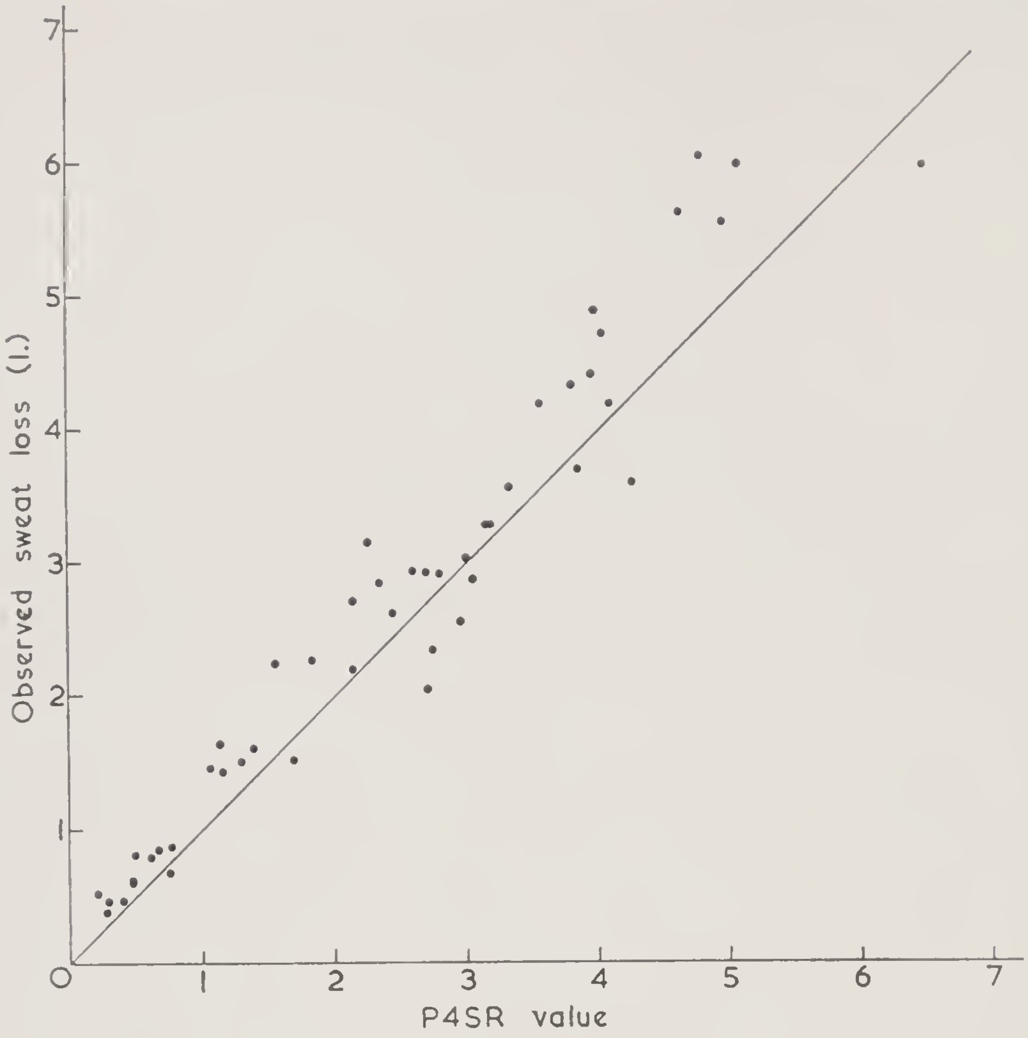

FIG. 2. Series II, Part 2 (post-acclimatization). Relation between observed sweat loss and calculated P4SR Index for all climate-work-clothing combinations. The line represents ideal (1:1) correspondence.

There is a marked similarity between all three equations and they closely resemble those found in Series I (Adam *et al.* 1952). These were as follows.

Series I Section A

$$Y = 2{\cdot}047 + 0{\cdot}9783(x - 1{\cdot}968) \qquad (6)$$

Series I Section B

$$Y = 1{\cdot}957 + 0{\cdot}9248(x - 1{\cdot}890) \qquad (7)$$

In all cases the slope of the line is very close to unity and in all cases Y has a small positive value when x is zero. But, despite these similarities, differences can be demonstrated between the several equations.

There is a significant difference between the slopes of the regression lines for Series II and III. Series III ($b = 0{\cdot}9342$) differs from both Series II Part 1 ($b = 1{\cdot}0630$) at the 1 per cent level and Series II Part 2 ($b = 1{\cdot}1440$) at the 0·1 per cent level. There is no significant difference between the slope of the two lines for Series II Part 1 and Series II Part 2. Similarly it may be shown that although the slopes of all three lines are very close to unity, that for Series III is significantly less than 1 at the 1 per cent level, that for Series II Part 2 is significantly greater than 1 at the 1 per cent level and that for Series II Part 1 does not differ significantly from 1.

This means that all three lines represent a difference in behaviour with respect to the P4SR as the rate of sweating increases. In the case of Series II Part 1 the

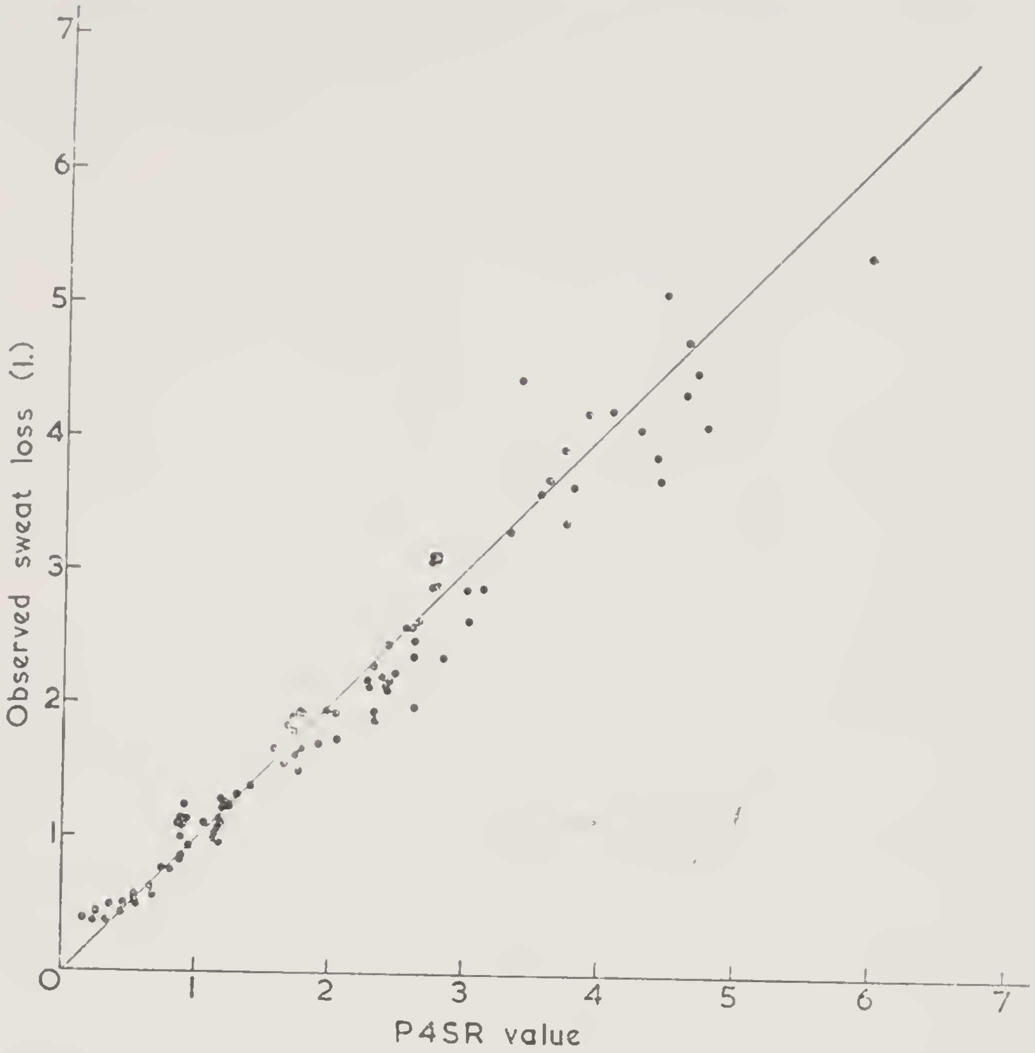

FIG. 3. Series III (Sections A & B). Relation between observed sweat loss and calculated P4SR Index for all climate-work-clothing combinations. The line represents ideal (1:1) correspondence.

difference between the P4SR and the sweat loss does not alter with increasing levels of environmental stress. In Series II Part 2 the amount by which the observed sweat loss exceeds the P4SR value tends to increase with increasing degrees of stress. In Series III at low levels of stress the observed sweat loss and the P4SR are very similar but at higher levels the P4SR values exceed the corresponding values for observed sweat loss. The differences just described are quantitatively small and it is difficult to say whether they are to be considered as indicating differences between the behaviour of the London subjects and the Singapore subjects that could reasonably be attributed to differences in acclimatization.

If Fig. 1, 2 and 3 are compared, an interesting difference between the two series of experiments becomes apparent. In the case of Series II, in both Part 1 and Part 2 by far the greater number of points lies above the line representing a one-to-one correspondence between the observed sweat loss and the P4SR value, but in Series III the position is reversed and the greater number of points lies below this line. In Series II the observed values are greater than the predicted values but in Series III the observed are less than the predicted values. The statistical significance of the mean difference between the observed sweat losses and the P4SR values at all climate-work-clothing combinations was tested by applying Student's '*t*' test to the mean value of the difference between each pair of values, i.e., by showing that the mean of the differences was significantly

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different from zero. The results are set out in Table 33. In Series I there is, on the whole, no significant difference between the observed sweat losses and the P4SR values. In both parts of Series II the observed sweat losses are significantly greater than the P4SR values. In Series III the observed sweat losses are significantly less than the P4SR values.

These differences, then, represent differences of level in the response of the several groups of men to hot environments. Such differences could be due to variations in the level of acclimatization of the groups concerned, but are clearly not so here. In the two parts of Series II the behaviour is the same (as would be expected from the findings on p. 33) despite the difference in acclimatization in the two parts, and the behaviour in Series III differs from that in Series II Part 2 though in both cases the men were highly acclimatized. It should be pointed out, however, that Series III was a much longer investigation than Series II Part 2 and, as will be seen later (p. 213), the rate of sweating in Series III declined progressively with time.

By far the most likely explanation lies in the fact that different groups of men produce different amounts of sweat under identical conditions. Some of the difference can be accounted for by differences in body size (see p. 90) but there remain other personal differences, the reason for which is still obscure. The subjects used in Series II were slightly heavier than those of Series III but this does not wholly explain the observed differences. The subjects used in Series II were by chance heavy sweaters. One subject, 'D', was particularly remarkable in this respect. At low levels of stress his behaviour was not greatly different from that of other members of the team, but at high levels of stress he was revealed as a veritable sudorific athlete and capable of producing up to 8 l. of sweat in 4 hr.

The more complex situation of the two referred to on p. 47 is that in which differences between groups of subjects are found to exist at some levels but not at others. In this case it is much more difficult than in the simpler case of a general difference in the level of response to decide whether or not the differences are due to differences in the level of acclimatization.

In the report on Series I (Adam *et al.* 1952) the observed sweat losses were compared with the P4SR values for the environments used and it was concluded that—

'This overall agreement is very striking . . . If its [the P4SR's] sole object was to predict the *average* physiological behaviour of a *large group of subjects* in a hot room, under controlled conditions, it would be hard to find a better substitute . . . It is perhaps remarkable that the behaviour of the Singapore subjects was so similar to that of the London subjects. Nevertheless there are significant differences for particular treatment combinations.'

In Series I, the analysis of the deviations from regression of the observed sweat loss on the P4SR value showed that the significant deviations from regression were associated with the amount of clothing worn, the rate of working and variations in the air speed. The most important divergence between observed and predicted values was that for the difference in sweat loss between men wearing shorts and men wearing overalls at dry-bulb 120° F. At this air temperature the discrepancy between the predicted difference and the observed difference was large and it increased with increasing air speed.

These findings are important and it is necessary to examine them in some detail. In Table 34 (taken from Adam *et al.* 1952) are set out the observed mean differences between the sweat losses of men wearing shorts and men wearing overalls and between working men and resting men, together with the mean differences expected on the basis of the regression equation relating the P4SR Index and the observed sweat loss in Series I.

At dry-bulb 90°F the nomogram consistently over-estimates the amount by which the sweat loss of men in overalls exceeds that in shorts by, on the average, roughly 280 g, and this amount is but little affected by changes in the air speed. On the other hand, the nomogram tends to under-estimate the amount by which the sweat loss of working men exceeds that of resting men. The actual amount of this under-estimation in general diminishes with increasing air speed, both at wet-bulb 80°F and at wet-bulb 85°F.

At dry-bulb 120°F, wet-bulb 80°F, the nomogram agrees with the observed result that men in overalls will produce approximately 400 g more sweat than men wearing shorts at an air speed of 20 ft./min. But whereas the nomogram would indicate that the amount of this difference remains constant with increasing air speed, the observed values indicate that, as the air speed increases, the amount of sweat lost by men wearing shorts comes to exceed that lost by men wearing overalls, and that at 500 ft./min the value of this difference is approximately 700 g, so that the discrepancy between the observed and predicted differences reaches almost 1100 g.

At dry-bulb 120°F, wet-bulb 85°F, a similar disagreement exists. At an air speed of 20 ft./min the observed and predicted values agree that men in overalls lose more sweat than men in shorts, and this is also true at 100 ft./min. At 300 ft./min the observed sweat loss in shorts exceeds that in overalls, although the nomogram would indicate that the value for overalls exceeds that for shorts. At 500 ft./min there is a similar discrepancy between the observed and predicted differences, which in this case amounts to almost 800 g.

The nomogram fails to recognise that at dry-bulb 120°F there is a 'crossing over' between shorts and overalls, which occurs at an air speed of approximately 300 ft./min at wet-bulb 85°F and at a lower air speed at wet-bulb 80°F.

At dry-bulb 120°F, as at dry-bulb 90°F, the P4SR under-estimates the amount by which the sweat loss of working men exceeds that of resting men. At dry-bulb 120°F, wet-bulb 80°F, as at dry-bulb 90°F, wet-bulb 80°F and 85°F, the discrepancy between the observed and predicted differences diminishes with increasing air speed. At dry-bulb 120°F, wet-bulb 85°F, there is no consistent trend with changes in the air speed.

These findings suggest that the P4SR does not predict the effect of variations in the amount of clothing worn and in the rate of working as accurately as, for example, it predicts the effect of changes in air temperature for a fixed work-clothing combination. Moreover, they suggest that the nomogram does not reflect accurately the effect of changing the air speed on the relative stress imposed by working and resting or by wearing shorts and wearing overalls, and that it is chiefly in error in this regard at the high air temperatures.

It is therefore necessary to examine the results of Series II and Series III to see whether they lend support to these conclusions. An analysis of variance was made of the deviations of the observed sweat losses from the calculated P4SR values. This approach differed slightly from that used in Series I where the analysis was performed on the deviations from regression. The former treatment is theoretically more desirable, but in practice the results are very similar in the two cases.

A brief summary of the results of these analyses is set out in Table 35. These results would appear to support the finding of Series I that the divergencies of the

P4SR Index from the observed sweat loss are associated chiefly with the rate of working, the amount of clothing worn and the interaction of air speed with these two factors.

The finding in Series I that, on the average, the observed difference between the sweat losses of men in shorts and men in overalls was much greater than the expected difference is consistent with a number of findings concerning observed and predicted values for shorts and overalls separately. It might be due to over-estimating the effect of overalls, or it might equally well be due to underestimating the effect of shorts. In order to interpret the findings concerning the differences between the effects of shorts and overalls and between the effects of working and resting, and the effects on these of changes in the air speed, it therefore becomes necessary to compare the observed sweat loss and the P4SR value at each combination of climate, work rate and clothing. This has been done for all three series (Series I, Series II (pre-acclimatization) and Series III) in Tables 36 and 37 and the same results are presented in graphical form in Fig. 4, 5, 6 and 7.

Comparisons within these results must be made with the greatest caution, especially those between series. For example, if the values for 'shorts working'

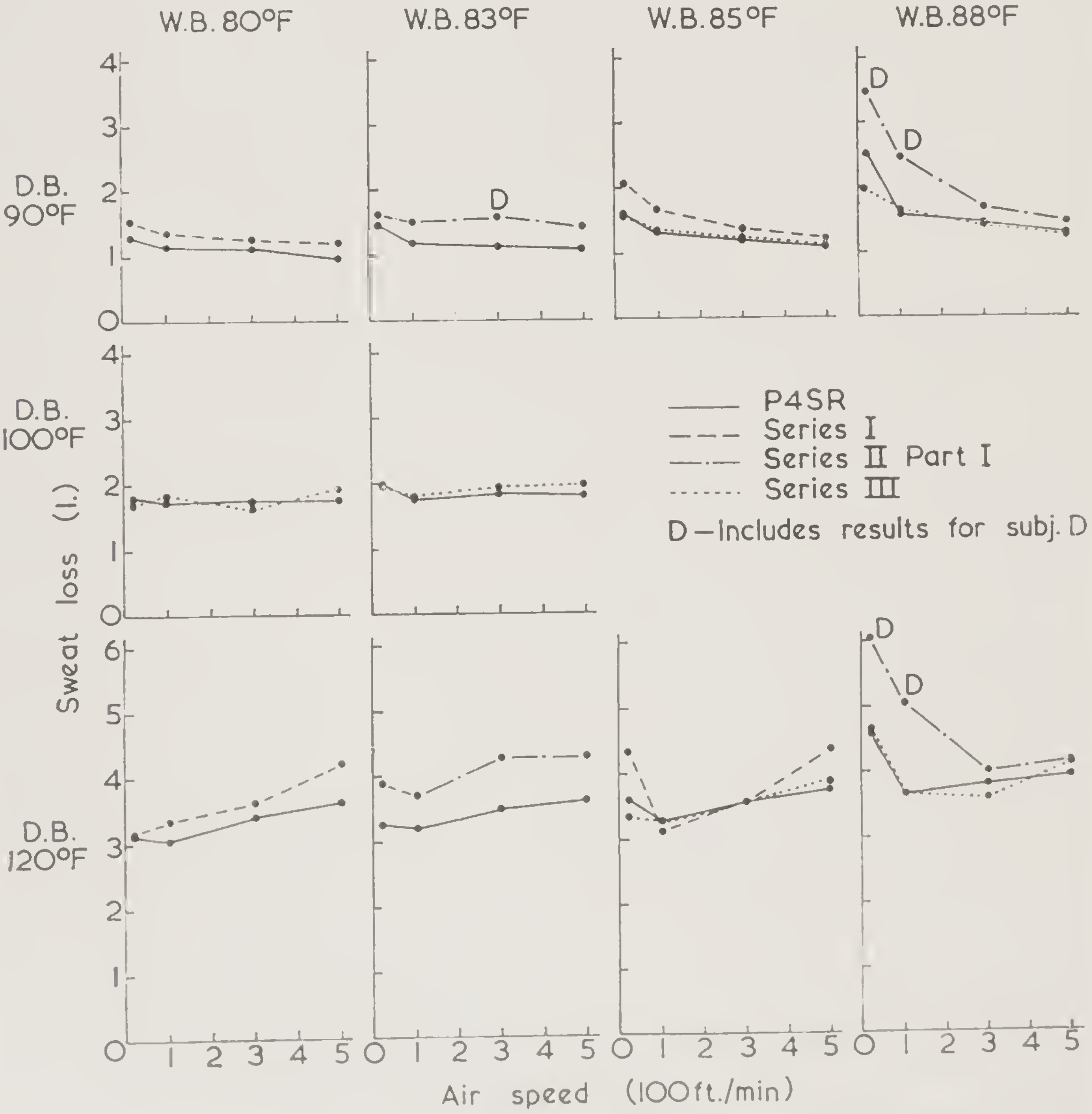

Fig. 4. Comparison of the observed sweat losses in Series I, II & III for men working in shorts at the various air temperatures, humidities and air speeds with those predicted by the P4SR nomogram.

at dry-bulb 90°F, wet-bulb 80°F in Series I are compared with the corresponding values at dry-bulb 90°F, wet-bulb 85°F in Series III it will be seen that the two sets of values are very similar indeed. It might be concluded that varying the wet-bulb temperature from 80°F to 85°F at dry-bulb 90°F is without effect on the sweat loss. Such a conclusion would be misleading. These two series were performed at different times on different individuals. Besides unexplained individual variation there will be variation due to the size of the subject and the amount of water drunk, as well as the important effect of the degree of acclimatization on sweat loss.

Comparison within series will be on much safer ground, but even here the position is not unassailable. For example, in Series II the same work-clothing combination was allocated at different climate combinations to different subjects, so that comparison here involves comparison between individuals. In Fig. 4, 5, 6 and 7 those environments in which subject D appeared are indicated by the symbol *D*. This subject, as mentioned above (p. 52) could sweat profusely. Examination of these figures will show that at low levels of stress, e.g., resting in shorts at dry-bulb 90°F, wet-bulb 83°F, the presence of D has little effect on the general level of results, but that at high levels of stress, e.g., working in

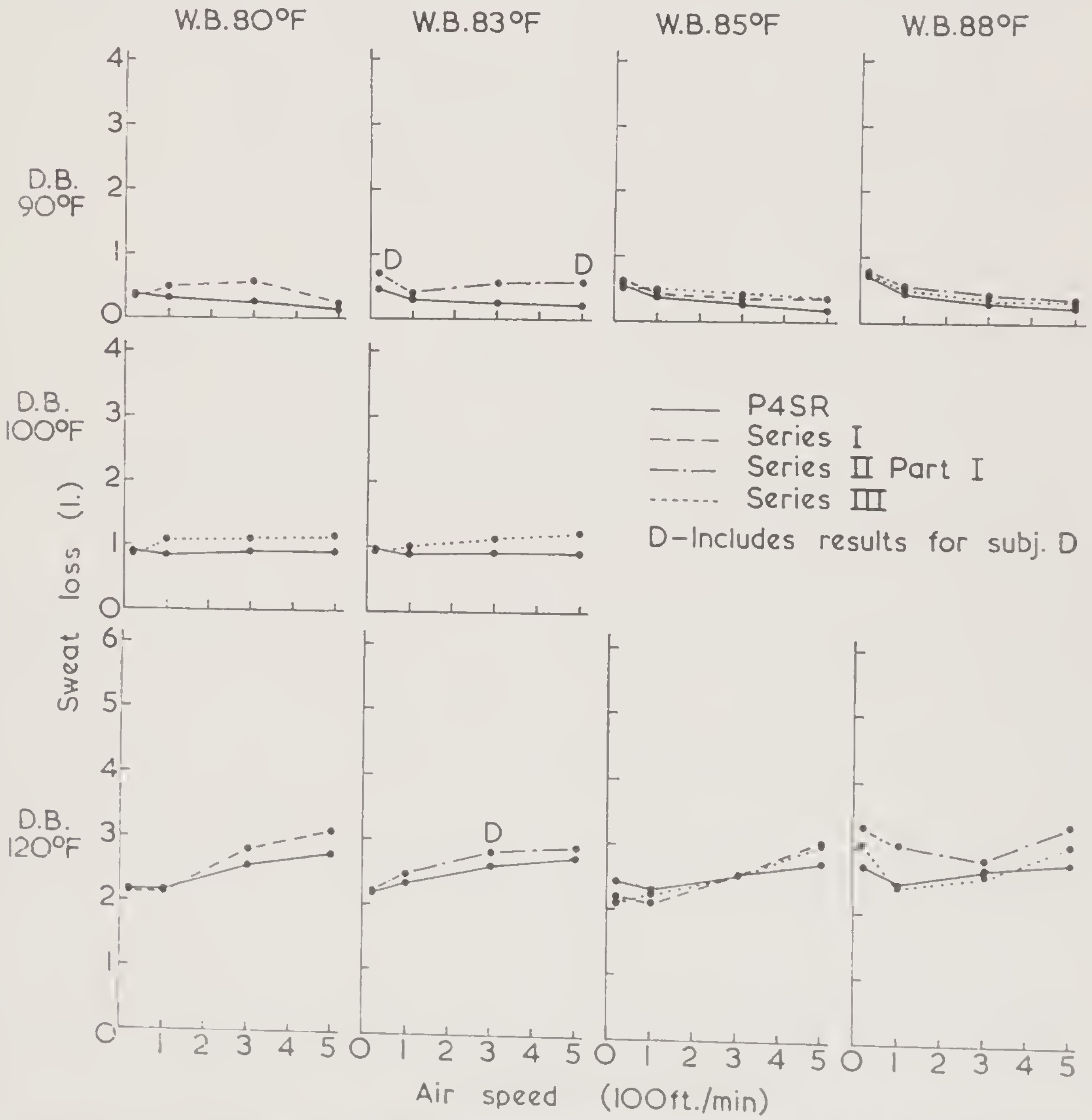

FIG. 5. Comparison of the observed sweat losses in Series I, II & III for men resting in shorts at the various air temperatures, humidities and air speeds with those predicted by the P4SR nomogram.

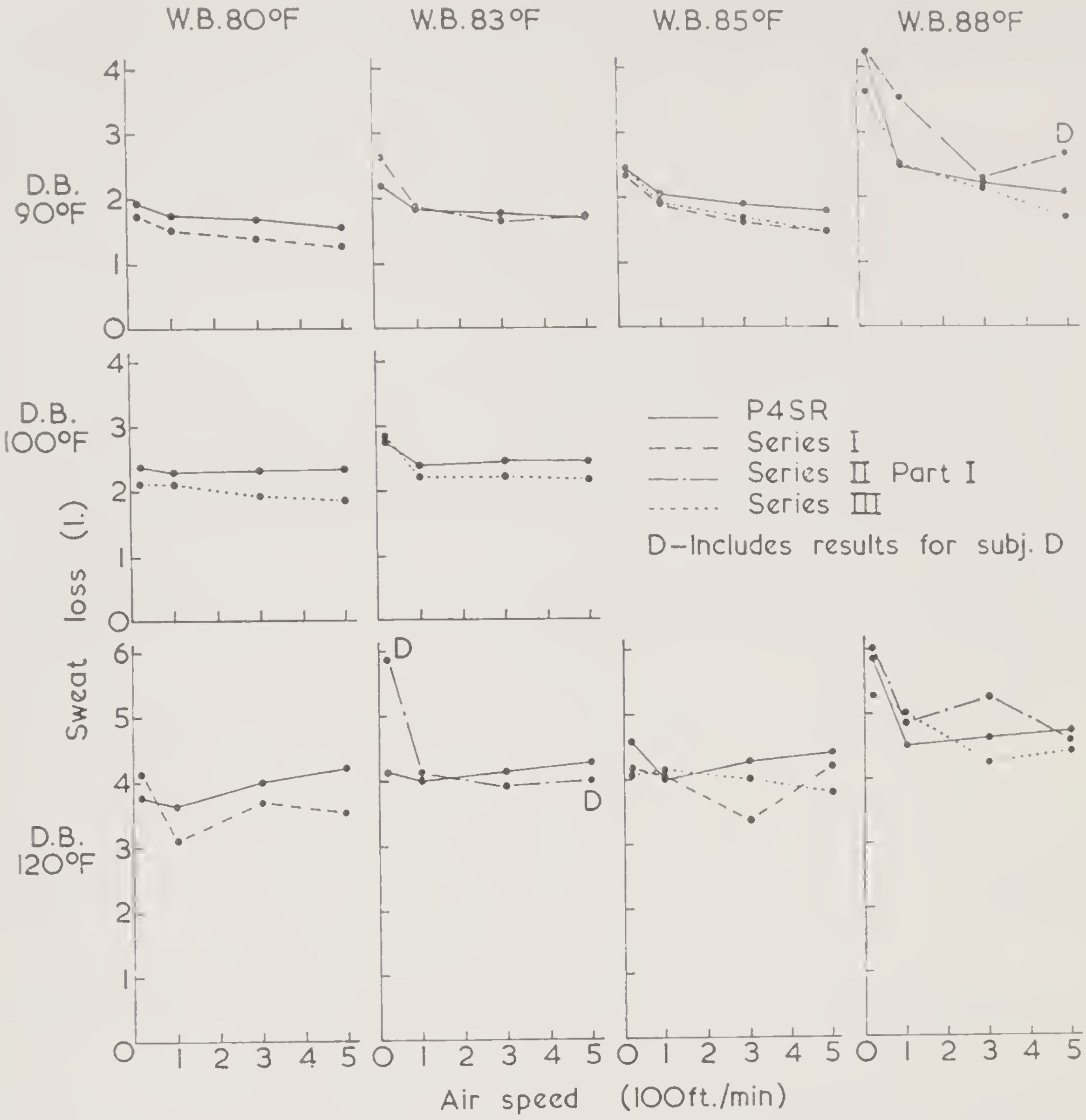

FIG. 6. Comparison of the observed sweat losses in Series I, II & III for men working in overalls at the various air temperatures, humidities and air speeds with those predicted by the P4SR nomogram.

shorts at dry-bulb 120°F, wet-bulb 88°F, the results which include those of D are greatly above the expected value. It is therefore clear that the greatest care should be exercised in interpreting the results, and that the conclusions drawn must be, of necessity, of the most general kind.

Table 34 and Fig. 4-7 show that in Series I at dry-bulb 90°F, wet-bulb 80°F the P4SR Index under-estimates the sweat losses of men in shorts and over-estimates the sweat losses of men in overalls. The net result is that the P4SR Index greatly over-estimates the difference between the effects of wearing shorts and wearing overalls, and, as is evident from the shape of the curves, this result is reasonably consistent at all air speeds.

The same state of affairs exists at dry-bulb 90°F, wet-bulb 85°F, but to a somewhat lesser extent. It is noteworthy that the values for Series III which are available for comparison at this wet-bulb temperature diverge less, on the whole, from the P4SR values than do the values for Series I. The suggestion at once arises that if these highly-acclimatized Series III subjects had performed experiments at dry-bulb 90°F, wet-bulb 80°F, their results would have again been more closely in agreement with the P4SR values. If this had been observed,

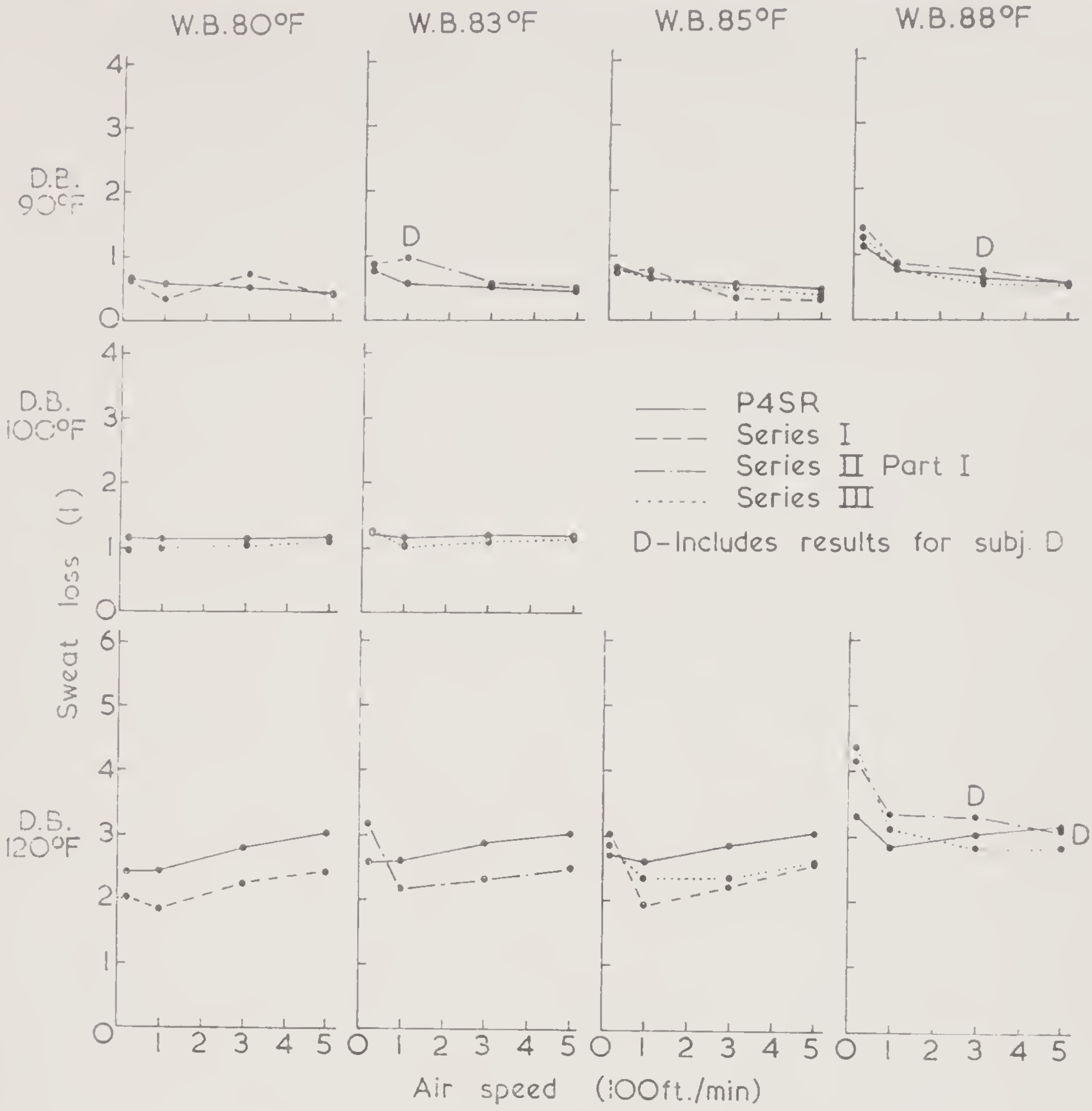

FIG. 7. Comparison of the observed sweat losses in Series I, II & III for men resting in overalls at the various air temperatures, humidities and air speeds with those predicted by the P4SR nomogram.

it would be considered that the differences at wet-bulb 80°F between the P4SR values and the Series I results were due to the difference in acclimatization status between the subjects of Series I and the London subjects on whose results the P4SR Index was based. There is, however, another possible explanation, viz., that in the P4SR Index incorrect allowance was made for the effect of changes in the wet-bulb temperature. Some support for this alternative but less likely explanation is afforded by the fact that,in general, the agreement between the observed values and the P4SR values improves (if the anomalous values undoubtedly due to subject D are neglected) as the wet-bulb temperature increases from 80°F to 88°F (Fig. 4–7).

In Series I at dry-bulb 120°F, wet-bulb 80°F and in Series II at dry-bulb 120°F, wet-bulb 83°F, the P4SR Index under-estimates the sweat loss of men wearing shorts and over-estimates the sweat loss of men wearing overalls, but this does not appear to hold at the higher wet-bulbs 85°F and 88°F. This observation is of importance as it leads to a consideration of the phenomenon of 'crossing over'.

This effect is well described in the words of Adam *et al.* (1952) who, in reporting Series I, state 'In general men sweat more when they wear overalls than when they wear shorts. The position however is reversed when the dry-bulb temperature is 120°F provided the air velocity is sufficiently high. The level of air movement where this reversal occurs is about 300 ft./min but varies with the wet-bulb temperature and the degree of activity of the subject'. This 'crossing over' is not confined to sweat loss. A similar phenomenon is observed in the rectal temperature and heart rate.

The occurrence of this phenomenon has been amply substantiated in Series III and is dealt with in detail in the statistical analysis (Table 22).

Table 34 shows that the P4SR Index fails to recognize this phenomenon. At dry-bulb 120°F, wet-bulb 80°F and air speed 20 ft./min, the sweat loss expected for men in overalls exceeds that expected for men in shorts by 440 g, which agrees well with the observed difference. With increasing air speed, the expected difference retains almost the same value but the observed difference alters, changing from negative to positive between 20 and 100 ft./min, and at 500 ft./min the sweat loss for shorts exceeds that for overalls by 664 g.

Table 36 confirms that the 'crossing over' occurs also in Series III at dry-bulb 120°F, wet-bulb 85°F, but shows that the effect is much greater for resting than for working men. At dry-bulb 120°F, wet-bulb 88°F in Series III, the phenomenon does not occur with working men, whose sweat loss is always greater in overalls than in shorts, and in the case of resting men it occurs only at the highest air speed, viz., 500 ft./min. At 100°F (Table 37) it is doubtful whether 'crossing over' occurs at all in the case of working men, even at the low wet-bulb temperatures of 80°F and 83°F, but it does occur with resting men, although the effect even here is not very marked (Table 24). At dry-bulb 90°F the phenomenon does not occur.

To sum up, it may be said that the P4SR Index fails to recognize the phenomenon of 'crossing over' and that the most important differences between the observed sweat losses and the P4SR Index are associated with this failure. This reversal with increasing air speed of the relative stress imposed by wearing overalls and by wearing shorts is not present at 90°F, but with increasing air temperature becomes apparent, being just recognizable at 100°F and well marked at 120°F; it is more marked at low humidities than at high humidities, for example at dry-bulb 120°F, wet-bulb 80°F it is more marked than at dry-bulb 120°F, wet-bulb 85°F; finally, it is more apparent in resting than in working men.

The findings in Series I, II and III with respect to the effects of variations in the air speed on the amount of sweat lost agree very well, in general, with the experimental findings of Dunham *et al.* (1946). However, these workers' interpretation of their findings—especially their rigid concept of two phases, under all conditions, in the effect of increasing the air speed—cannot be entirely agreed with. Such a description tends towards over-simplification of a very complex phenomenon. It may be added that Dunham and his colleagues make no mention of the effects of 'crossing over'.

Direct Comparison of Sweat Losses in London and Singapore

A number of the treatment combinations used by Dunham *et al.* (1946) at the National Hospital occur also in Series III. It is therefore possible to make direct comparisons between the two groups of subjects for those treatments which are common to the two groups. The environments were not always exactly the same, especially as regards air speed, but were close enough for the results to be comparable, except perhaps at low air speeds when the air temperature was 120°F. Under these conditions the wall temperatures (and hence the globe thermometer readings) at Singapore tended to be slightly below air temperature and there was a corresponding reduction in the level of environmental stress.

The comparison is summarized in Table 38. Inspection of this table shows at once the similarity between the sweat losses in the two groups of men. A satisfactory objective test of significance for the difference between them would require a much more exact specification of the way in which individual subjects vary in their responses to hot environments than is possible at present. It can be said, however, that such differences as exist are, for the most part, quite consistent with the individual variation shown at Singapore, and cannot be taken as indicating a real difference between the behaviour of men artificially acclimatized in London and that of men artificially acclimatized in Singapore over the range of conditions investigated.

At dry-bulb 120°F, there does seem to be some tendency for the London results to be higher than those at Singapore. The apparent exception at dry-bulb 120°F, wet-bulb 88°F for men working in overalls must presumably be taken to indicate a reduced capacity for sweating in the two London subjects, since it would appear unlikely that increasing the wet-bulb temperature from 85°F to 88°F would lower the sweat loss.

One other result which requires comment is that for men working in shorts at dry-bulb 90°F, wet-bulb 88°F, and air speed 20 ft./min. Here, the average effect on the two London subjects of reducing the air speed from 100 ft./min to 20 ft./min is greater than the effect on any of the subjects in Series III, but the difference could be due to a single exceptional value in London. The only differences between the two groups which must almost certainly be regarded as statistically significant are those for men working in overalls at dry-bulb 120°F. However, this may be accounted for partly by the differences in the wall temperatures previously noted and partly by the differences which exist between individuals.

For those environments in which the amount of sweat loss in the Singapore experiments differs from the corresponding P4SR values, the London results of Dunham *et al.* (1946) usually agree more closely with those in Singapore than with the P4SR values. The one notable exception to this general statement is in the case of men working in shorts at dry-bulb 90°F, wet-bulb 88°F, and air speed 20 ft./min. Here the London results agree with the P4SR Index rather than with the Singapore results. In general, for men wearing overalls the London results tend to support the Singapore results rather than the P4SR Index—except for men working at dry-bulb 120°F, wet-bulb 85°F. It is particularly important to observe that for men resting in shorts at an air speed of 500 ft./min at air temperatures of 100°F and 120°F, the London results and the Singapore results agree in that they are considerably higher than the corresponding P4SR values. This supports what has been said previously concerning the P4SR Index and the phenomenon of 'crossing over'.

Rectal Temperature, Pulse Rate and the P4SR Index

The results of Series III provide three separate measures of the stress of the climate-work-clothing combinations examined—sweat loss, rectal temperature and pulse rate. It remains to be seen if these separate measures are in agreement one with another and, further, in those cases in which the P4SR Index differs from the observed sweat loss, which of the two is most closely supported by the heart rate and the deep body temperature.

Mean final rectal temperatures and mean final standing pulse rates both correlate well with the P4SR Index over the range of conditions examined in Series III. The correlation coefficients are respectively 0·88 and 0·94. Table 39 shows the observed means of the final rectal temperatures and the values predicted from the P4SR Index, using the estimated regression equation

$$Y = 98{\cdot}74 + 0{\cdot}5099x$$

where y is the rectal temperature in °F, and x is the P4SR value in litres. This relation should be compared with that given by McArdle *et al.* (1947): 'The increase in rectal temperature in °F at the end of a four-hour period in a warm or hot environment may be predicted in acclimatized individuals by multiplying the P4SR by 0·4. An approximate estimate of the actual rectal temperature may be made by adding this increase to the arbitrary figure of 98·7°F'. The present findings differ in that the estimate of the final rectal temperature exceeds that of McArdle by 0·1 times the P4SR Index. The constant term 98·74 in the equation does not, of course, represent an estimate of the initial rectal temperature.

Table 39 shows that the observed and predicted values appear to be in satisfactory agreement, but it also reveals a difference between the responses of working and resting men. According to the regression equation, all climate-work-clothing combinations having the same P4SR value should result in the same final rectal temperature, irrespective of whether the subject is working or resting. It will be seen, however, that for any given P4SR value the observed final rectal temperature is always higher in working than in resting men.

This is also true for any given observed sweat loss, i.e., if two groups of men, one working and the other resting, have the same sweat loss, the mean final rectal temperature of the working group is always higher than that of the resting group.

When the relation of the observed sweat loss and the observed final rectal temperature is examined separately for working and resting men, the regression equations connecting the two are found to be

$$Y_1 = 98{\cdot}88 + 0{\cdot}5377x_1$$
$$Y_2 = 98{\cdot}87 + 0{\cdot}3156x_2$$

where x_1 and x_2 are the sweat losses of working and resting men respectively.

The explanation of the difference between these two relations is not altogether clear. No doubt it is in part due to the fact that in resting men the body temperature is relatively constant throughout the greater part of the four-hour period, but in working men it rises and falls with work and rest, and the final temperature is measured at the end of a period of work. In the case of the working man the final temperature will, in general, be considerably in excess of the average temperature for the experiment, to which, it is to be presumed, the amount of sweat lost in the four hours is related. In the case of the resting man, however, the final rectal temperature will be more closely related to the average temperature. A possible alternative explanation is based on the view of Nielsen (1938) that there is an appropriate body temperature, independent of the environment, for a given rate of work—the higher the rate of work, the higher the body temperature. This would suggest that a given rise of body temperature in the case of the working subject represents a smaller divergence from the 'set' value than that represented by the same rise of temperature in a resting man, and, in consequence, a reduction in the associated sweat loss.

Table 40 shows the observed means of the final pulse rate and the values predicted from the P4SR Index using the estimated regression equation

$$Y = 67{\cdot}2 + 17{\cdot}47x$$

where y is the final pulse rate in beats/min and x the P4SR value in litres.

There is on the whole good agreement between the observed and the predicted values, but, as was the case with the final rectal temperature, and probably for the same reason, for any given P4SR value or observed sweat loss, resting men have lower pulse rates than working men.

This indication by the pulse rate and rectal temperature of differences between the responses of resting and working men is the chief systematic difference between the estimates of environmental stress provided by the P4SR on the one hand and by the pulse rate and rectal temperature on the other. (It is most readily apparent at the highest dry-bulb temperature, 120°F.) The P4SR Index and the sweat loss are, in general, in agreement, so that this difference reflects a difference between the effects of the treatments on sweat loss and the effects on the other physiological variates. The probable reason has already been given.

There are other differences of this kind. For example, men wearing overalls at dry-bulb 120°F have both slower pulse rates and lower sweat losses at air speeds of 300 ft./min or more than at lower air speeds. At these lower speeds, the rise in pulse rate—and rectal temperature—of such men, which occurs even at 100 ft./min, is observed at both wet-bulb temperatures 85°F and 88°F. However, the corresponding rise in sweat loss is observed only at wet-bulb 88°F; at 85°F there is no increase in sweat loss at low air speeds for men wearing overalls at dry-bulb 120°F.

Finally, where there are differences between the observed sweat loss and the P4SR Index, i.e. where the phenomenon of 'crossing over' occurs (pp. 57–8), it is found that the pulse rates and rectal temperatures agree more closely with the observed sweat loss than with the P4SR Index.

In only one case in Series III is the P4SR Index greater than 5, viz. for men working in overalls at dry-bulb 120°F, wet-bulb 88°F, and air speed 20 ft./min. Under these conditions the observed sweat rates are lower than expected, but the pulse rate is about equal to expectation and the rectal temperature is much higher than the expected value.

The conclusions seem to be that except in certain cases the final rectal temperature and the pulse rate confirm the measure of environmental stress provided by the observed sweat loss. They are, however, less precise measures than sweat loss, so that it is only possible to say whether they support the P4SR or the observed sweat loss when there are large differences between these two. Where such differences exist when the P4SR value is less than 5, it would seem that the P4SR scale falls short of its ideal.

Diurnal Variation in Rectal Temperature

One of the particular aims of Series III was to determine the nature and degree of the differences which might exist between the results of experiments performed in the morning and in the afternoon. Although there was some evidence that the effects of air temperature and work rate on sweat loss were slightly greater in the morning in Section A of Series III, and the effect of increasing the humidity seemed to be slightly greater in the afternoon in Section B, in general the morning-afternoon effect on the rate of sweating was not significant. The findings concerning rectal temperatures were in marked contrast to these. Rectal temperatures were definitely higher in the afternoon than in the morning. Before the subjects entered the climatic chamber the difference was 0·53°F, but at the end of the third work period it was only 0·15°F for Section A and 0·28°F for Section B. These findings have been discussed elsewhere (Macpherson, 1956) where it was shown that this effect was dependent upon the well known diurnal temperature rhythm occurring in man as well as in other mammals and in birds, and accords well with the findings for the variations in diurnal temperature observed by Adam and Ferres (1954), which are discussed in Chapter 9.

Effective Temperature and Thermal Stress

It has been pointed out in Chapter 2 that the P4SR Index was introduced in part because the workers at the National Hospital considered that the widely used Effective Temperature Scale failed to give an accurate measure of the relative stress of different hot environments. Benson *et al.* (1945) claimed that this scale over-emphasized the effect of the dry-bulb temperature as opposed to that of the wet-bulb temperature, and under-emphasized the effect of low air speeds in contributing to the stress of hot environments. Dunham *et al.* (1946) claimed that the Effective Temperature Scale failed to indicate the deleterious effects of low air speeds at high humidities and that at air temperatures above body temperature it indicated an amelioration of conditions with increasing air speed instead of an improvement followed by a deterioration.

Adam *et al.* (1952) examined these claims at length, using as a measure of the environmental stress the sweat losses, final rectal temperatures and pulse rates of the subjects in Series I. The conclusions were as follows. 'If each work-clothing combination is taken separately the predictive accuracies . . . of the Effective Temperature Scale and the Predicted Four-hour Sweat Rate nomogram . . . are about the same though there is a slight advantage to the latter in predicting sweat loss. However, when the results of all groups of experiments are combined, correlations with effective temperature are considerably lower than with the predicted four-hour sweat rate. This is due to the fact that the Effective Temperature Scales make no allowance for differences in work rates.They were not designed to do so, being intended originally only for comparisons when clothing and work conditions were held constant. In this sense predicted four-hour sweat rate is a more comprehensive index. It also gives a more adequate picture of the change in stress with air movement. In hot conditions effective temperature does not allow adequately for the reduction in stress as the air velocity is increased to 100 ft./min and indicates too great an improvement at 200–500 ft./min. On the other hand, the concept of the predicted four-hour sweat rate can only be applied within the range of climate-work-clothing combinations which cause people to sweat. It cannot replace effective temperature under the more comfortable and desirable conditions of light and sedentary work, with which it was designed to deal primarily, for sweating will not occur under these conditions'.

The experimental results obtained at the National Hospital were re-examined by Smith (1952). He concluded

> 'the results bear out the criticisms made of effective temperature. They also show that the P4SR scale is the more accurate scale for predicting sweat rate; yet, when the magnitude

> of the possible error of predicting individual sweat rate is considered, the difference between the two scales is not striking. It seems possible too, that by eliminating the anomalies, the accuracy of the Effective Temperature Scale could be improved at the higher levels. Although the data examined here are sufficient to show that anomalies exist, they are not adequate for use in attempting adjustment of the Effective Temperature Scale.
>
> 'It also appears practicable to indicate the effect of work at the higher levels of effective temperature. However, more experimental data are necessary because the anomalies need to be eliminated before an accurate relationship can be established between sweat rate and effective temperature for various work levels'.

In view of these findings it might seem pointless to pursue the question further, but there are nevertheless some good reasons for so doing—at any rate briefly. Apart from the general doubt concerning the acclimatization status of the men used in Series I, and the considered opinion of the authors of the report on this series that further investigations should be made to confirm or refute their findings, there was in addition one important point raised by the results of Series I. The findings in this series were quite contrary to those of Benson *et al.* (1945) in that they showed that the Effective Temperature Scale over-emphasized the effect of the wet-bulb temperature rather than that of the dry-bulb temperature. (Benson *et al.* (1945) had criticized the Effective Temperature Scale on the grounds that it had over-emphasized the dry-bulb temperature). Clearly, this point required settling beyond all doubt.

It was only to be expected that, with the passage of time, the skill and experience of the observers would increase and the experimental methods become more refined. For this reason it was thought that Series III probably provided a somewhat more reliable body of data than Series I and that this was an added justification for another attempt to assess the value of the Effective Temperature Scale as an index of stress.

It has been suggested (as indeed the quotation from Adam *et al.* (1952) above might be taken to imply) that it is not entirely correct to use the Effective Temperature Scale as a measure of environmental stress for conditions such as those of the Singapore experiments.

Regarding the correctness of applying the Scale to the range of temperatures, humidities and air speeds used in Singapore, there can be no serious doubt. Although the first steps in the devising of the Scale were concerned with establishing equal comfort lines (Houghten & Yagloglou, 1923*a*), its originators made it clear that it could be used in conditions of temperature and humidity where to speak of comfort is a misnomer (Houghten & Yagloglou, 1923*b*). Air velocity, though not at first incorporated, was included in the later versions of the Scale over a range extending well beyond that used in Singapore (Houghten & Yagloglou, 1924; Houghten, Yagloglou & McConnell, 1924; Yagloglou & Miller, 1924; Yagloglou, 1927).

As far as the clothing used in the Singapore experiments is concerned, the shorts and overalls can be said to correspond reasonably, if not perfectly, to the clothing conditions for which the two versions of the Scale were devised. The original version, the 'Basic' Scale, was intended for use with men stripped to the waist, wearing light trousers, shoes and socks—a reasonable, but unfortunately not an exact, equivalent of the shorts at Singapore. The 'Normal' Scale, which was developed later (Yagloglou & Miller, 1925), relates to men 'normally clothed', a condition which conforms closely to that of the subjects wearing overalls.

Where levels of activity are concerned, although the Scales are unquestionably applicable to the resting conditions in the experiments, their application to the working conditions does admittedly present difficulties. The 'Normal' Scale was intended for application to men only 'slightly active' and the 'Basic' Scale was intended to apply specifically to men at rest (Yagloglou & Miller, 1925), though later the application of both Scales to working subjects was investigated (Houghten, Teague & Miller, 1926).

It would seem, then, despite the difficulties noted, that it is justifiable to apply the Effective Temperature Scale in the conditions of these experiments. Nevertheless, the appraisal of a scale based on sensations of comfort by reference to other measures of physiological effect such as sweat loss, body temperature and pulse rate may appear questionable. However, its originators were insistent (Houghten & Yagloglou, 1923*a*; Houghten, Phillips & McConnell, 1923; Yagloglou & McConnell, 1924) that all points on the same line of equal comfort (effective temperature) produced the same degree of physiological effect as measured by just these variables.

The assessment of effective temperature as an index of environmental stress will be confined here to an examination of the accuracy with which effective temperature can be used to predict the amount of sweat lost, which, of course, involves the assumption that sweat loss is a measure of environmental stress.

Sweat Losses and Effective Temperature

The equations relating the sweat losses observed in Series III and the corresponding effective temperatures were calculated and found to be as follows:

For 'shorts working'

$$Y = 0{\cdot}01516x^2 - 2{\cdot}429067x + 98{\cdot}578$$

For 'shorts resting'

$$Y = 0{\cdot}013906x^2 - 2{\cdot}247624x + 91{\cdot}379$$

For 'overalls working'

$$Y = 0{\cdot}011074x^2 - 1{\cdot}654323x + 62{\cdot}552$$

For 'overalls resting'

$$Y = 0{\cdot}026353x^2 - 4{\cdot}408729x + 185{\cdot}064$$

where y is the sweat loss in litres and x is the corrected effective temperature of the environment, using the 'Normal' Scale for overalls and the 'Basic' Scale for shorts. It will be seen that four such equations are required to represent the two levels of work and the two levels of clothing. It will also be noted that the relation between the Effective Temperature Scale and the sweat loss, unlike that between the P4SR Index and the sweat loss, is not linear. The curves represented by these equations have been plotted, those for shorts in Fig. 8 and those for overalls in Fig. 9.

If Fig. 8 and Fig. 9 are compared it will be seen that the line representing the sweat loss of resting men in overalls on the 'Normal' Scale of effective temperature agrees very closely with that for resting men wearing shorts on the 'Basic' Scale of effective temperature.

This is a very interesting finding, but it can only be regarded as fortuitous, and as probably occurring only in the range of conditions investigated here. Adam *et al.* (1952) have stated that it does not follow that at an effective temperature of, say, 70 F on the 'Basic' Scale a man stripped to the waist will feel as warm as he will when he is clothed and the effective temperature on the 'Normal' Scale is 70 F. Ferres, Fox, Jack, John, Lind, Macpherson & Newling (1954) have further emphasized this point. They pointed out that at a temperature of 80°F

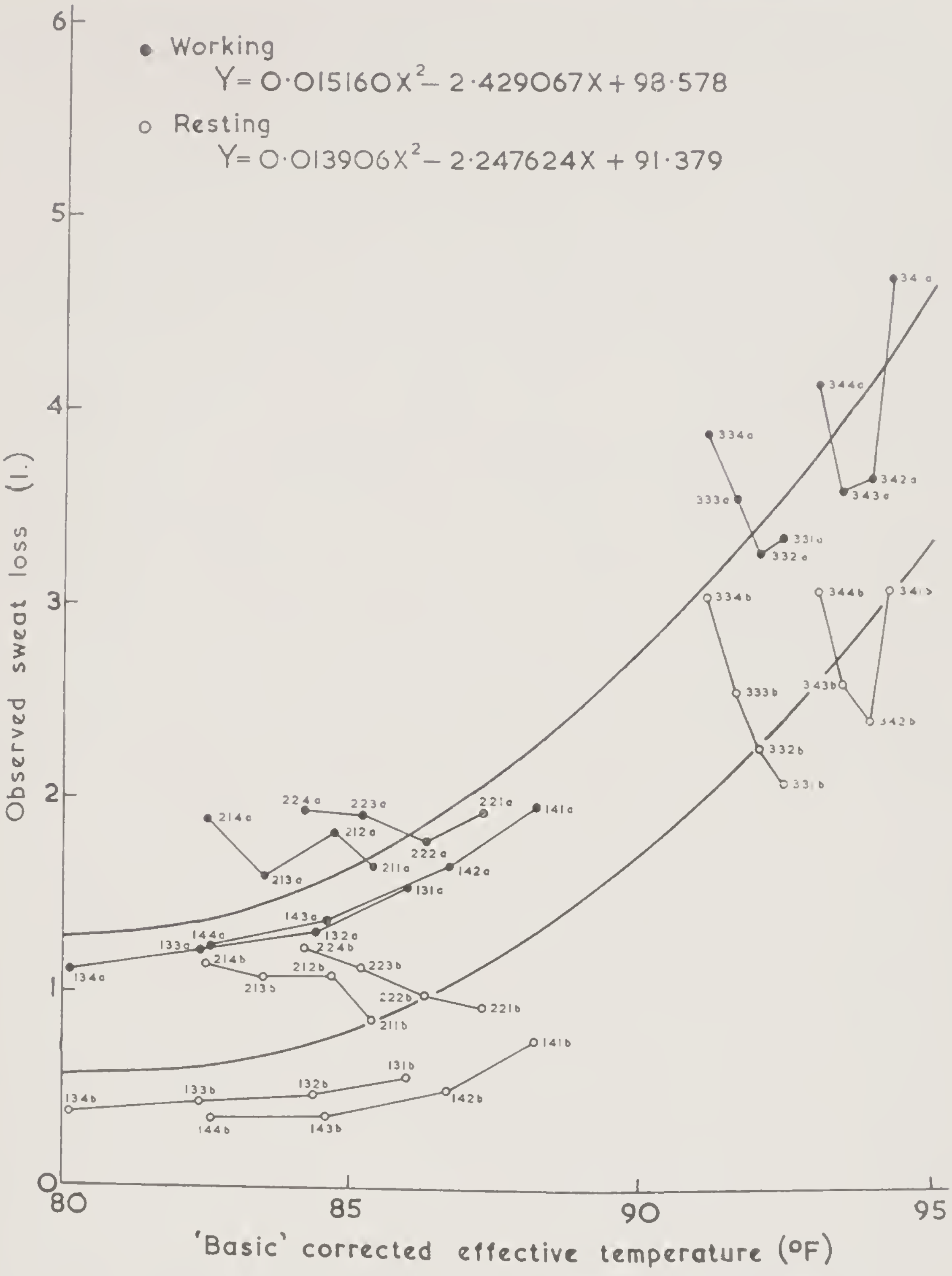

FIG. 8. Series III. Relation between observed sweat loss for men wearing shorts and 'basic' corrected effective temperature. Points representing different air speeds at the same air temperature and humidity are joined. The symbols used to identify each point are explained in the text.

on the 'Basic' Effective Temperature Scale a man stripped to the waist experiences the same degree of comfort as he would in a saturated atmosphere at 80°F. Similarly, a man wearing light indoor clothing at 80°F on the 'Normal' Effective Temperature Scale would experience the same degree of comfort as he would when wearing the same clothing at a saturated temperature of 80°F. Clearly, however, the degree of comfort experienced at a saturated temperature of 80°F would differ a great deal with the two types of clothing.

The plotted points in Figs. 8 and 9 are the means of the observed sweat losses at each climate-work-clothing combination and can be identified by the following four-symbol code. The first numeral refers to the dry-bulb temperature—

1, 2 and 3 indicate respectively 90°F, 100°F and 120°F. The second numeral refers to the wet-bulb temperature—1, 2, 3 and 4 are respectively 80°F, 83°F, 85°F and 88°F. The third numeral refers to the air speed—1, 2, 3 and 4 indicating 20, 100, 300 and 500 ft./min respectively. The letters a, b, c and d indicate the work-clothing combinations in the order shorts working, shorts resting, overalls working and overalls resting.

By tracing the lines on the diagrams which connect points representing conditions in which the air temperature, humidity, rate of work and clothing are kept constant but the air speed is varied, it will be seen how complex the effect of varying the air speed is. The effect of a given change depends not only upon

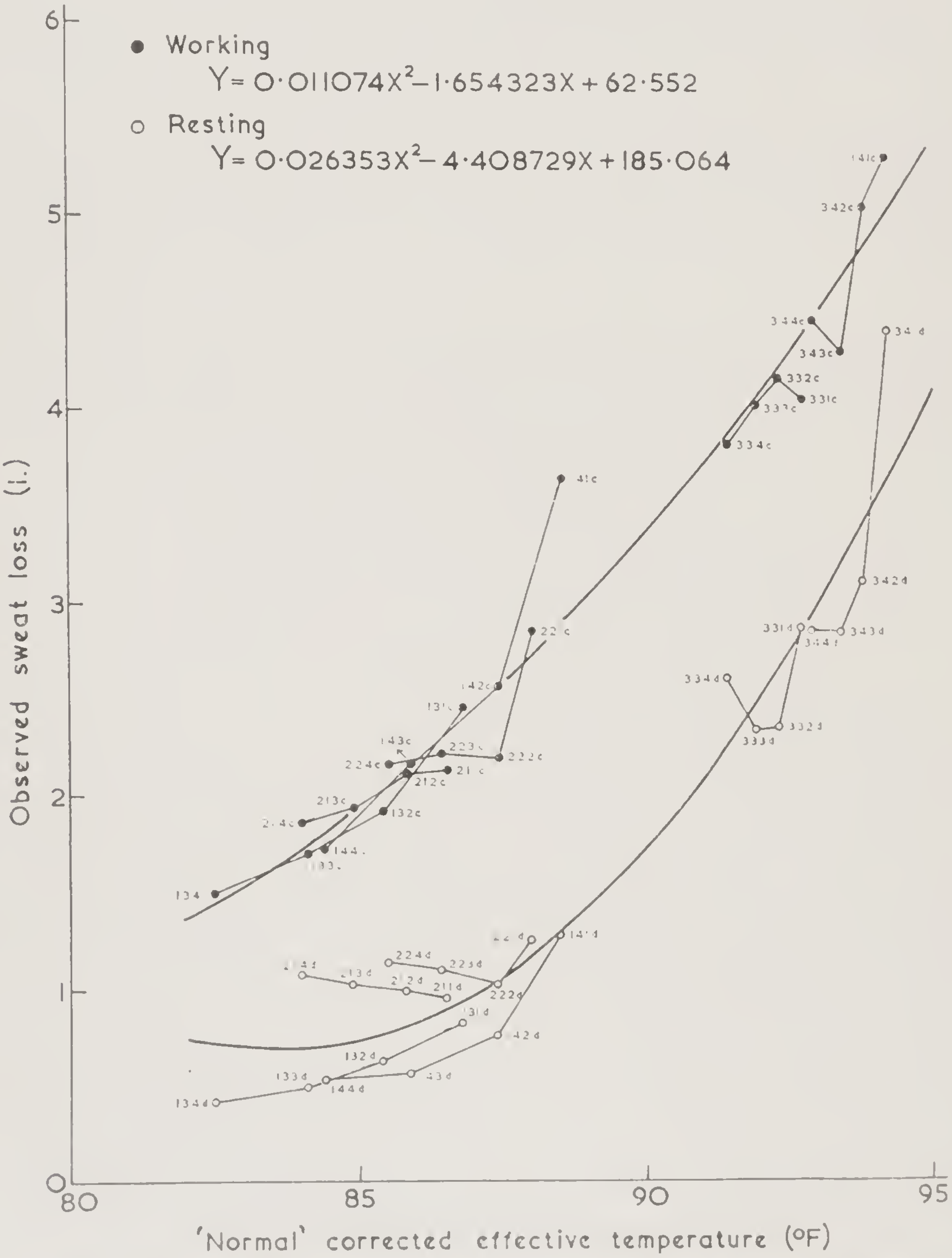

FIG. 9. Series III. Relation between observed sweat loss for men wearing overalls and 'normal' corrected effective temperature. Points representing different air speeds at the same air temperature and humidity are joined. The symbols used to identify each point are explained in the text.

the air temperature, humidity, rate of work and clothing but also upon the existing value of the air speed at which the change is made.

This strongly supports the contention of the workers at the National Hospital that the Effective Temperature Scale is in error in indicating that the effect of increasing the air speed is a constant improvement in conditions and that the relation is almost linear. For example, it will be seen from Fig. 8 that whereas the 'Basic' Effective Temperature Scale indicates that at dry-bulb 100°F conditions are improved as the air speed is increased this is not borne out by the experimental results. On the contrary, with increasing air speed the sweat losses tend to increase. At dry-bulb 120°F the effective temperature indicates an improvement in conditions with increasing air speed, whereas the observed sweat loss increases steeply—with or without an initial fall, depending on the work rate and humidity. At dry-bulb 90°F, however, especially for working men, the Effective Temperature Scale represents more closely the effect of changing air speed, as with increasing air speed the sweat losses decline.

Fig. 9 shows that there are comparable differences for men in overalls between the observed sweat loss and the 'Normal' Effective Temperature Scale. These differences are somewhat dissimilar in pattern to those observed for men in shorts between the sweat loss and the 'Basic' Effective Temperature Scale, and tend to be smaller than them. The closer agreement between the observed and predicted values for men in overalls is perhaps explained in part by the fact that overalls worn over shorts provide a closer approximation to the 'light indoor clothing' to which the 'Normal' Scale refers than do shorts alone to the 'stripped-to-the-waist' condition to which the 'Basic' Scale applies.

The relation between the sweat losses in Series III and the Effective Temperature Scale does not, however, support the conclusions of Benson *et al.* (1945) that 'the Effective Temperature Scales in very hot environments over-emphasize the part played by the dry-bulb temperature as opposed to that played by the wet-bulb temperature in contributing to the stress'. It tends rather to support the contrary view expressed by Adam *et al.* (1952) that it is the effect of the wet-bulb temperature rather than that of the dry-bulb temperature which is over-emphasized by the Effective Temperature Scale. For example, in Fig. 8 the values for both resting and working men wearing shorts at dry-bulb temperature 90°F and at wet-bulb temperatures 85°F and 88°F lie below their representative curves. On the other hand, the values at dry-bulb 100°F and wet-bulb 80°F and 83°F tend to lie above the appropriate curves, so that at dry-bulb 100°F men sweat more than at the same effective temperature at dry-bulb 90°F. This may be expressed in the terms used by Benson *et al.* (1945) by saying either that the Effective Temperature Scale under-emphasizes the effect of increasing the dry-bulb temperature from 90°F to 100°F as opposed to the effect of reducing the wet-bulb temperature from 88°F to 83°F and from 85°F to 80°F, or by saying that it over-emphasizes the ameliorating effect of thus reducing the wet-bulb temperature as opposed to the pejorative effect of the increase in the dry-bulb temperature. The contrary view expressed by the Queen Square workers was due to the consideration of a special case and though true for the example chosen is not true in all cases.

Upper Tolerable Levels of Warmth

In the report on Series I (Adam *et al.* 1952) considerable attention was devoted to the problem of defining the upper tolerable levels of warmth and, using the relation between the observed body temperatures and the pulse rates at the end of the four-hour experimental periods and the sweat losses predicted by the P4SR nomogram, the authors concluded that these levels were represented by a P4SR Index of 3·5. By this was meant that as this value for the climate-work-clothing combination is exceeded, an increasing number of men will be unable to complete the four-hour task. This was to apply only to men in the same state of acclimatization as the subjects of Series I and to conditions comparable with those of the experiments. As it was desirable that some margin of safety be provided, it was concluded that the upper levels of warmth to be permitted under action conditions in ships should not exceed those for which a P4SR Index of 3·0 is predicted.

It was hoped that both Series II and Series III would provide further information on this important question. It was expected that comparison between the behaviour of the subjects before, and their behaviour after, acclimatization in Series II, and comparison of the behaviour of the naturally acclimatized subjects of Series I and the highly acclimatized subjects of Series III would be especially valuable.

However, experiments of the kind performed in Singapore do not lend themselves readily to the determination of upper tolerable limits. The only sure way of determining whether a given set of conditions is tolerable or intolerable is to expose a group of men to these conditions and observe the results. Extremes of conditions, of course, present no difficulty; the difficulty exists in defining the boundary between those which are tolerable and those which are intolerable. This is further complicated by the fact that time is one of the parameters which must be considered in defining tolerability. For example, conditions that are tolerable for a limited period, and which may again be tolerable after a period of relief in less rigorous conditions, may be intolerable for longer periods of continuous exposure. Conclusions that are based on four-hour exposures can therefore be applied only to periods of four hours. Information from such experiments is, however, not without value because experiments designed to determine tolerable levels are most unpleasant for the subjects and not without some element of danger, so that any information gained is worthy of study.

The most unsatisfactory aspect of the use of experiments such as those of Series II and Series III to explore tolerable limits lies in the fact that, if the limits of tolerability for any subject should be exceeded and he fails to complete an experiment, the experimenter is faced with the problem of missing values. Although statistical techniques exist for the computation of missing values, none can be considered as entirely satisfactory. It is, of course, with those conditions that approach intolerable levels that the experimenter is chiefly concerned, and for which it is most desirable that the reactions of the subjects be precisely measured. The most satisfactory procedure, therefore, in designing such experiments is to arrange that the higher levels of stress used should approach, but not exceed, those that are tolerable. Subjects vary among themselves and it happens that when the limits of tolerance are approached some subjects will fail and some will complete the experiment, but if the main purpose of the experiment is not to be defeated the number of failures must be kept small.

In Series II there were twenty-eight occasions on which subjects failed to complete a four-hour exposure. Some conclusions can be drawn from an analysis of the conditions in which these failures occurred, although such conclusions, for reasons that will become apparent, can only be tentative. Of the twenty-eight occasions, seventeen occurred in the pre-acclimatization period and eleven in the post-acclimatization period. This might at first sight appear to provide some measure of the effects of acclimatization, but it must be remembered that neither the range of conditions nor the number of exposures was the same in the two parts of the experiment. There is some evidence, however, that acclimatization did increase the range of conditions which could be tolerated.

Only one failure occurred at dry-bulb 90°F and that was a somewhat unexpected failure in an acclimatized man working in overalls at dry-bulb 90°F, wet-bulb 88°F, air speed 20 ft./min. His rectal temperature reached only 101·3°F and he was incapacitated largely by severe abdominal cramps—a possible case of heat cramps due to salt deficiency. All other failures occurred at a dry-bulb temperature of 120°F, and all occurred in working men (Table 41), but it is most important to remember that the subjects in these experiments were never expending even as much energy as that expended by a man walking at 4 m.p.h. unloaded, and that the rate of energy expenditure is one of the most important of the environmental stresses.

The remaining ten failures in the post-acclimatization period occurred when the dry-bulb temperature was 120°F and the wet-bulb temperature 88°F. There were no failures when the humidity was below this value. Of the ten failures, five occurred when the air speed was 20 ft./min, two occurred at air speed 100 ft./min and three occurred at air speed 300 ft./min. Of the five failures at 20 ft./min, three men were wearing overalls and two were wearing shorts. At the two higher air speeds, only one man failed when wearing shorts and he was suffering from an alcoholic 'hangover'. The conclusion that can be drawn from these findings is that when the dry-bulb temperature is 120°F the upper limit of tolerability is reached at or below a wet-bulb temperature of 88°F under certain specific conditions. The conditions are that the subjects have been previously acclimatized to high temperatures, have the general physical fitness of the subjects examined in these experiments, are working at a level of 110 $\text{kcal.m}^{-2}.\text{hr}^{-1}$ and are wearing the appropriate clothing.

All seventeen failures in the pre-acclimatized state occurred at dry-bulb 120°F—ten when the wet-bulb temperature was 88°F, two at wet-bulb 85°F and five at wet-bulb 83°F. Of the ten failures which occurred at wet-bulb 88°F, six occurred at air speed 20 ft./min, three at air speed 100 ft./min and one at air speed 500 ft./min. Three men out of the six who failed at 20 ft./min were wearing shorts.

The most interesting feature here is that failures occurred at humidities represented by a wet-bulb temperature of less than 88°F. This would suggest that the tentative conclusions drawn may now be extended somewhat by saying that at dry-bulb 120°F the upper limit of humidity for men naturally acclimatized to tropical conditions is somewhat less than that for men who have been artificially highly acclimatized, and probably is about 83°F under the conditions which have been described.

There is some other evidence, too, concerning the relative degree of acclimatization of the two groups of subjects. In each group, ten subjects failed at dry-bulb 120°F, wet-bulb 88°F. The average rectal temperature of the subjects in the pre-acclimatization group was 103·3°F and the highest temperature recorded was 104·2°F. In the post-acclimatization group the average temperature was 102·1°F and the highest temperature recorded was 103·2°F. It is difficult to determine the exact meaning of these findings. They may merely mean that the level of distress which was considered to indicate that conditions were intolerable was lower in the second part of the series than in the first. For this reason too it is not wise to make too exact comparisons between Series II and Series III. Standards can easily alter with time.

In Series III only seven cases of serious heat incapacitation occurred. In all cases the dry-bulb temperature was 120°F and the wet-bulb temperature 88°F. The air speed was 20 ft./min in five cases and 300 ft./min in the remaining two. The men were working and all wore overalls except one who failed at dry-bulb 120°F, wet-bulb 88°F, air speed 20 ft./min. There were other cases of temporary disability that did not prevent the subject from completing his four-hour period in the hot room. These were usually cases of near syncope in men rising after sitting still, and they occurred even at dry-bulb 90°F, wet-bulb 88°F. They were more common in men wearing overalls than in men wearing shorts.

In Table 42 are set out the P4SR Indices of those environments used in Series II in which at least one man failed to complete the four-hour experiment. The lowest value at which a failure occurred among the highly acclimatized men was 3·83 (dry-bulb 120°F, wet-bulb 88°F, air speed 100 ft./min, shorts working), and among the naturally acclimatized men it was 3·33. This would appear to provide substantial support for the conclusion of the authors of Series I that as the stress of the environment exceeds that represented by a value of 3·5 on the P4SR scale, an increasing number of men possessing the degree of acclimatization to heat to be expected in men serving in ships in tropical waters will be incapacitated.

At the conclusion of these series of experiments it was felt that the question of upper tolerable limits required further investigation and experiments designed solely to this end were conducted. These experiments have been reported by Ellis, Ferres, Lind and Newling (1953), and will be described in Chapter 8.

Acclimatization

Much attention has been given to the physiological changes that accompany repeated exposure to high temperature. The changes that have been reported have recently been reviewed (Bass, Kleeman, Maliszewski, Macleod, Quinn, Dobalian and Pillion, 1953) and it is clear that there is still much disagreement among authors. Some of this disagreement can perhaps be explained by the fact that the periods during which subjects have been observed have varied in length. These periods have usually been short and for this reason it was considered extremely important that advantage should be taken of the long period (5 months) spent by the subjects in the performance of Series III to determine whether the more prominent physiological adjustments which take place during continuous daily work at high temperature were, in fact, confined to the first 14 days or so of such exposure, or whether there was a continuing effect as suggested by the results of Series II. In order to achieve this end, despite the disadvantages of lengthening further an already lengthy experiment, uniformity trials were held at short intervals throughout the whole length of Series III.

The results of these experiments have been reported separately (Adam, Ellis, John, Lee & Macpherson, 1953) and they will be referred to again in Chapter 10. Suffice it to say here that they revealed that there was a long-term physiological adjustment to hot environments not previously recognized, differing in important respects from the commonly recognized short-term adjustment, and that they clearly indicated the need for further information on this aspect of acclimatization.

From the point of view of Series II it is more important to emphasize not the changes which occur over a long period of time but rather the rapidity with which changes can occur in the behaviour of subjects. In this series there was a marked change in the rate of sweating between the beginning and the end of the first part of the experiment, despite all the precautions that were taken to preserve the naturally acclimatized state of the subjects.

It is impossible to give a completely satisfactory definition of acclimatization. Bass *et al.* (1953) define it as 'A process of adaptation to work in the heat with lessened subjective discomfort and increased efficiency', but such a definition gives no hint as to what this process of adaptation involves. The triad usually accepted as indicative of acclimatization to heat is an increased rate of sweating, a diminished heart rate and a lower body temperature on exposure to heat stress. Of these three, it is clear that the fundamental effect is the lower deep body temperature, and this perhaps should be taken as the true measure of the effectiveness of the acclimatization process. Series II clearly demonstrates that the lower body temperature and the increased sweat rate are not causally related. There was at first an increase in the rate of sweating without an accompanying increase in body temperature, and later a lowering of the body temperature without further change in sweating rate. It is clear that the increased sweat rate cannot be taken by itself as a measure of acclimatization. In Series III, after the initial rise in sweat rate there was a decline with time—as there appeared to be, to some extent, in the last part of Series II. The most interesting feature is the ease with which the increased rate of sweating is provoked.

The lability of the sweat rate provided the chief obstacle to the accomplishment of one of the main purposes of Series II—the measurement of the responses of naturally acclimatized men. It cannot be said with certainty that the acclimatization status of the subjects was not altered by the performance of the first part of the series. For this reason the matter was later investigated using another type of approach which will be described in the following chapter.

Summary

1. Series III was concerned chiefly with the quantitative evaluation of the effects of variation in the several factors of temperature, humidity, air speed, metabolic rate and clothing. The results of Series I and Series II had made it clear that the only way in which an exact measure of the effects of variation in the level of these factors could be obtained was to use as subjects men who had been brought into a stable state by an adequate period of training for work at high temperatures and humidities, i.e., men who were artificially maximally acclimatized.

2. Series III, as finally planned, consisted of two distinct experiments. Section A comprised all combinations of two levels of air temperature (90°F and 120°F), two levels of wet-bulb temperature (85°F and 88°F), four levels of air speed (20, 100, 300 and 500 ft./min), two levels of energy expenditure (50 and 110 kcal.m^{-2}.hr^{-1}) and two levels of clothing. Section B consisted of all combinations of one air temperature (100°F), two levels of wet-bulb temperature (80°F and 83°F), and the same levels of air speed, energy expenditure and clothing as in Section A. The experiment proper was preceded by a period of intensive acclimatization. This period of acclimatization was preceded and followed by uniformity trials. Uniformity trials were also conducted at regular intervals throughout the experiment proper.

3. The effect of variations in the various factors was estimated in terms of the total amount of sweat lost, and the levels of both rectal temperature and pulse rate after the third and after the final work period. A systematic statistical analysis of the results is given.

4. It was found that the effect of increasing the air temperature, the humidity, the rate of working, or the amount of clothing worn is to increase the amount of sweat lost, the rectal temperature and the pulse rate. No simple quantitative expression can be given for the effect of unit change in any one of these factors, as the effect of changing from one level to another in any factor depends upon the level of the remaining factors.

5. The effect of changing the air speed is extremely complex and may result in an increase or in a decrease in the amount of sweat, the rectal temperature and the pulse rate, according to the level of the remaining factors. At low air temperatures (90°F and below), increasing the air speed always has a beneficial effect. At higher air temperatures (above 100°F), the effect may be beneficial or the reverse depending upon the humidity, the rate of working and amount of clothing worn. The general effect is at first an improvement in conditions but, as the air speed increases beyond a certain limit, the increased convectional gain outweighs the improvement in evaporative heat loss. The point at which this transition occurs varies. In general, the higher the air temperature the lower the air speed at which improvement ceases. The higher the humidity and the rate of work, and the more clothing worn, the higher the level at which improvement of conditions ceases and deterioration sets in. Thus at relatively low air temperatures and high humidities, with heavy clothing and high rates of energy expenditure, increasing the air speed to quite high values gives progressive improvement in conditions as the speed is raised. At high air temperatures and low humidities, with low rates of working and light clothing, increasing the air speed beyond even 50 ft./min may produce a deterioration in conditions.

6. The observed sweat losses in Series II and Series III were plotted against the sweat losses predicted by the P4SR nomogram. The regression equations obtained were very similar to those obtained by Adam *et al.* (1952) for Series I. They indicated that on the whole there was very good agreement between the predicted and the observed sweat loss. There were some differences. The sweat losses in both parts (pre-acclimatization and post-acclimatization) of Series II were on the whole greater than those predicted by the P4SR. On the other hand, the sweat losses in Series III were less than those predicted. Possible reasons for this are discussed and it is concluded that the explanation is probably not the respective degree of acclimatization of the two groups but the variation which occurs in the rates of sweating of different individuals treated alike.

7. The sweat losses at all climate-work-clothing combinations were examined separately and compared with the losses predicted by the P4SR Index. The discrepancies found to occur between the predicted sweat loss and the observed sweat loss in Series I were confirmed. It is shown that they are due to an inexact prediction of the effect of varying the air speed. The complex effect has been described in paragraph 5 above. It is to be stressed, however, that on the whole the P4SR predicts the sweat loss with remarkable accuracy.

8. Direct comparison of the sweat losses in Series III with those observed by Dunham *et al.* (1946) in London showed that, for the same environmental conditions, the results were very similar for the two groups of subjects. For those

environments in which the amounts of sweat lost in the Singapore experiments differed from the corresponding P4SR values, the London results usually agreed more closely with those in Singapore than with the P4SR values.

9. Comparison of rectal temperature, pulse rate and sweat loss as indices of environmental stress showed good agreement between all three measures, except that, for any given sweat loss, working men had higher pulse rates and rectal temperatures than resting men. When the observed sweat loss differed from the P4SR value, the rectal temperature and pulse rate usually supported the sweat loss rather than the P4SR value. At climate-work-clothing combinations with the same P4SR value, working men had again higher pulse rates and rectal temperatures than resting men and in this the P4SR was in agreement with the observed sweat loss.

10. In Series III all climate-work-clothing combinations were investigated twice, once in the morning and once in the afternoon. Comparison was made of the results obtained in the morning with those obtained in the afternoon in order to determine whether the time of day affected the findings. No significant effect was found for sweat loss or for pulse rate. In the case of the rectal temperature, there was a significant difference between the morning and afternoon results. The rectal temperature of the subjects before they entered the climatic chamber was 0·52°F higher in the afternoon than in the morning, but at the end of the third work period it was only 0·15°F higher in Section A and 0·28°F in Section B. This finding agrees well with the hypothesis that any alteration in the rectal temperature produced by the stress of the environment is additive to the effect produced by the naturally-occurring diurnal variation in body temperature. This result is of importance as it indicates that values for the rectal temperature obtained in experiments at different times of day are not comparable unless allowance is made for the effect of the diurnal rhythm in body temperature.

11. An attempt was made to assess the value of the Effective Temperature Scale as a measure of the physiological strain produced by hot environments. It was shown that when the 'basic' and 'normal' scales of effective temperature are used for men wearing shorts and men wearing overalls respectively, the Effective Temperature Scale correlates well with the observed sweat loss for a given rate of work. A different relation holds for each level of work. The relation between the effective temperature of the environment and the sweat loss, unlike that between the P4SR Index and the sweat loss, is non-linear. The Effective Temperature Scale does not represent correctly the effect of varying the air speed at high air temperatures. It indicates, instead of the complex relationship found to exist, consistent improvement in conditions with increased air speed.

12. The findings of Series I (Adam *et al.* 1952) that the Effective Temperature Scale over-emphasizes the effect of increasing the wet-bulb temperature and under-emphasizes the effect of increasing the dry-bulb temperature, under the conditions at which they tested it, were confirmed. (These findings were contrary to those of the workers at the National Hospital who stated that the Effective Temperature Scale tends to over-emphasize the effect of the dry-bulb temperature compared with that of the wet-bulb temperature.)

13. In Series III and the post-acclimatization section of Series II, failures to complete the four-hour experimental period were confined (except for one failure in Series III at dry-bulb 90°F, wet-bulb 88°F) to environments at dry-bulb 120°F, wet-bulb 88°F. All the subjects who failed were 'working' subjects,

although some wore overalls and others shorts. Failures were most numerous at the lowest air speed. In the pre-acclimatization period of Series II there were failures not only at dry-bulb 120°F, wet-bulb 88°F, but also at the lower levels of stress represented by dry-bulb 120°F, wet-bulb 85° and wet-bulb 83°F.

14. The behaviour of the highly (artificially) acclimatized men in Singapore was similar to that of the artificially acclimatized men used in the experiments in London, which would suggest that all these groups possessed approximately the same degree of acclimatization. The behaviour of the 'pre-acclimatization' group at Singapore provides some measure of the extent to which the 'natural' acclimatization of men serving in ships in tropical waters falls short of the degree of acclimatization which can be artificially acquired in hot climatic chambers.

15. As the lowest level of stress at which the naturally acclimatized subjects failed to complete experiments was represented by a P4SR Index of 3·3, it would appear that the conclusions in the report on Series I that the upper tolerable limits for such men are represented by conditions with a P4SR Index of 3·5, and that, where possible, conditions should not be allowed to exceed 3·0 on the P4SR scale, are sound.

16. Information on the long-term physiological adjustments to hot environments was gained by the use of 'uniformity trials' at regular intervals throughout Series III. The results of these trials are discussed in Chapter 10.

CHAPTER 5. THE NATURE AND DEGREE OF NATURAL ACCLIMATIZATION

An account of the work of J. M. Adam, J. W. Jack, R. T. John, R. K. Macpherson, P. S. B. Newling and P. S. You

The Experiments of Series IV

The series of experiments described in the last chapter (Series III) could be regarded as establishing with some degree of certainty the response to hot environments of artificially acclimatized men. Furthermore, by using such men as a carefully standardized human yardstick, it provided a measure of the effect of variations in the levels of the major components of environmental stress. In these two aspects it accomplished a great deal of the task of 'checking' the findings of the workers at the National Hospital, but there remained the outstanding question of the extent to which these findings on artificially acclimatized men could be applied to men who possessed only the degree of acclimatization that is acquired by residence in the tropics. That this was probably less than the maximum that could be achieved by artificial means was indicated by Series I, and amply substantiated by the effects of the period of artificial acclimatization which preceded Series III.

Any attempt to study the behaviour of naturally acclimatized men over a range of hot conditions is beset, as Series I and Series II clearly showed, by one important difficulty—the act of measuring their reactions itself alters their degree of acclimatization. If such subjects are made to work in a hot environment so that their reactions may be tested, they acquire in the process a further degree of acclimatization, and consequently their behaviour on a second occasion will differ from that on the first.

Even a single exposure to work in the heat can produce a measurable alteration in the reactions of a subject (Dreosti, 1935) and if this effect is to be avoided entirely it means that a subject must be used once only and then discarded. If this is done, then a further difficulty arises when attempts are made to compare the effects of various levels of the environmental factors. Comparisons must be made between different subjects, and the differences between the effects of climates are confounded with differences between subjects. This difficulty can only be met if an adequate method can be devised for correcting for the differences between subjects.

The problems with which the fourth series of experiments conducted at Singapore was concerned—the degree of acclimatization of men living in the humid tropics and the nature or pattern of their response to environmental stress—required for their solution, therefore, that a satisfactory method for the correction of differences between subjects should be devised. This, in its turn, led to some consideration being given to the source of these differences. This series of experiments (Series IV) was described by Adam, Jack, John, Macpherson, Newling and You (1953).

METHODS

It has already been pointed out (p. 29) that if it is desired to compare the reactions of two groups of men to hot environments it is necessary to make comparisons over a wide range of conditions, as differences may occur at some combinations of environmental factors and not at others.

In order to avoid as far as possible the effect of repeated exposures to hot environments and yet, at the same time, make possible a comparison of the effects of different levels of climatic stress, it was decided to use a large group of men and expose each man twice only with a standard interval between the two exposures. On the first occasion, all men were treated alike in a uniformity trial. The results of this trial were used to correct, by means of the technique of analysis of covariance, for differences between individuals when, on the second occasion (the factorial experiment), small groups were exposed to various hot environments.

Experimental Design

In the factorial experiment, there were four factors, each at two levels. These were:

D (dry-bulb temperature)—D_1, 90° F; D_2, 120° F;
W (wet-bulb temperature)—W_1, 80° F; W_2, 85° F;
A (air speed)—A_1, 20 ft./min; A_2, 300 ft./min;
P (activity and clothing)—P_1, sitting in shorts; P_2, working in shorts.

There were thirty-two subjects, S_1–S_{32}. The plan of the experiment was as follows:

D_1								D_2							
W_1				W_2				W_1				W_2			
A_1		A_2		A_1		A_2		A_1		A_2		A_1		A_2	
P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
S_1	S_3	S_5	S_7	S_9	S_{11}	S_{13}	S_{15}	S_{17}	S_{19}	S_{21}	S_{23}	S_{25}	S_{27}	S_{29}	S_{31}
S_2	S_4	S_6	S_8	S_{10}	S_{12}	S_{14}	S_{16}	S_{18}	S_{20}	S_{22}	S_{24}	S_{26}	S_{28}	S_{30}	S_{32}

Subjects

The subjects were thirty-two volunteers from among the crews of ships in Singapore. The restrictions imposed were that they should be medically fit, between the ages of 18 and 25 years, of 'average' weight, height and other physical characteristics, and that they should have had from 9 to 18 months tropical service in the tour of duty they were then serving. In order to prevent the group from containing men who were of widely different degrees of acclimatization by virtue of their ship-board duties, the further condition was imposed that they should all be engaged in comparable duties on their ships, e.g., they should either all be seamen or all be stokers. In this case, all the men were seamen. Although it proved impossible to meet entirely the requirements set out above, the subjects finally chosen did constitute a homogeneous group who approximated reasonably to the requirements; their characteristics were:

	Mean	*Range*
Age (yr)	20·9	18·5 – 29
Height (cm)...	171·97	164·78 – 179·39
Weight (kg)...	65·575	56·215 – 85·630
Surface area (m^2)	1·773	1·620 – 2·031
Period in tropics (months)	17·59	7 – 23

Allocation of Treatments

Although it was considered unlikely that a single exposure to a climate of only moderate severity in the uniformity trial would produce a profound change in the reactions of the men, nevertheless, in order to keep the effect as small as possible, it was arranged that 3 days should intervene for each man between his participation in the uniformity trial and in the factorial experiment.

This required some care in the arrangement of the experiment and the following procedure was adopted. Four men reported on the evening of Day 1 and spent the night under supervision. The morning of Day 2 was spent in a medical examination, indoctrination and training in the routine of the experiment. In the afternoon they underwent the uniformity trial. They were then discharged to their ship. On the evening of Day 2 a further four men reported and were treated in the same way. On the evening of Day 3 a further four men reported and were treated similarly. On the evening of Day 4 the first group of four subjects returned and spent the night under supervision; on the following morning they underwent the experiment allotted to them. On the evening of Day 5 the second group reported, and so on. This arrangement ensured that as far as possible the conditions of the experiment were standardized and that the trial proper was conducted at the same interval (3 days less 4 hours) after the uniformity trial for all subjects. The order in which the treatments were applied was random and the subjects were chosen for sitting and working by lot.

Experimental Procedure

The experimental procedure used was that of Series III, with these modifications. The working subjects were weighed, to determine their sweat loss, before and after each period of work and in the middle of the long rest period between the third and fourth work periods. The resting men were also weighed at the corresponding intervals. At the same times, rectal temperatures and pulse rates were measured as in Series III but, in addition, skin temperatures were measured as described below. All subjects wore shorts. The experimental routine was as follows:

Time (min)	
–20	Rest outside climatic chamber
–5	Pulse rate; rectal temperature
0	Enter chamber; weighed naked; don clothing; sit on stool
5	Skin temperatures
10– 40	'Work I'*
40	Measurements; drink 500 ml. water
50– 60	Rest seated
60	Measurements
70–100	'Work II'*
100	Measurements; drink 500 ml. water
110–120	Rest seated
120	Measurements
120–160	'Work III'*
160	Measurements; drink 500 ml. water
170–185	Rest seated
185	Measurements
195–210	Rest seated
210	Measurements
220–240	'Work IV'*
240	Measurements; leave chamber

* During these periods the subject either remained seated (the lower level of activity, P_1) or step-climbed (the higher level of activity P_2, also used in the uniformity trials).

Measurements: pulse rate; skin temperatures; rectal temperature; naked weight.

The temperature of the skin was measured at twelve points on the body—forehead, index finger, forearm, arm, front and back of chest, loin, abdomen, outer and inner thigh, calf and the dorsum of the great toe. The average skin temperature of the body was then taken to be the arithmetic mean of these twelve readings. This is essentially the method of Hardy and DuBois (1938), differing chiefly in the simplified method used for computing the average skin temperature.

The temperature of the skin at each point was measured with a copper-constantan thermocouple (26 s.w.g.) mounted on a specially designed V-shaped plastic carrier. Double cold junctions were used and the resulting e.m.f. was measured with a potentiometer with which changes as small as 5 μV could be detected. The couples were calibrated both in a water bath and on a heated surface and the two methods gave identical results. In applying the thermocouple, care was taken to secure intimate contact with the skin but to avoid excessive pressure.

A further important modification of the experimental procedure introduced in this series of experiments was that the fluid intake was standardized. Each man was given 500 ml. of water to drink at 50, 110 and 170 minutes after entering the hot room, so that in all 1·5 l. of water were drunk by each man during the experiment.

The Uniformity Trial

The uniformity trial was conducted at a dry-bulb temperature of 100°F, a wet-bulb temperature of 85°F, and an air speed of approximately 100 ft./min. The men wore shorts, and the experimental routine was that followed by working men in the factorial experiment.

RESULTS

Sweat Loss

The uniformity trial. The mean sweat loss (grams) was as follows.

Mean	*Range*	*Standard deviation*	*Standard error*
2181	1832–2710	223	40

The points to observe are that the range is very considerable—the highest value recorded was some 50 per cent in excess of the lowest value—and that the mean value, 2181 grams, was considerably in excess of the calculated P4SR value of 1·85 litres for this environment. The source of the variation between individuals is discussed on pp. 89-93. The individual values for the sweat loss in the uniformity trial are set out in full in Table 43.

The factorial experiment. The sweat losses in the factorial experiment were corrected by means of the technique of analysis of covariance. The observed values and the corrected values are set out in full in Table 44.

An analysis of variance was performed on the corrected values and the results are summarized as a table of mean values in Table 45.

All the main effects of climate and 'rate of working' (level of activity) were highly significant—sweat losses were uniformly greater at the higher levels of air temperature, humidity, air speed and activity. The increases in dry-bulb temperature and rate of work produced by far the most marked effects.

These direct effects, however, probably are of less importance than those represented by the first order interactions. All the first order interactions were significant except that of air temperature and rate of work (D × P). As can be seen from Table 45 the effect of the higher dry-bulb temperature was much greater at the higher air speed than at the lower, and a little greater at the higher wet-bulb temperature than at the lower. Similarly, the effect of working was considerably greater at the lower air speed than at the higher, and also greater at the higher humidity than at the lower. It is somewhat surprising to find that the level of dry-bulb temperature had no effect on the increase in sweat loss resulting from working rather than resting.

The effect of change of air speed is important. At 90°F an increase in the air speed resulted in a fall in the amount of sweat produced. At 120°F an increase in air speed resulted in an increase in the sweat loss. On the average, an increase in the air speed resulted in an increase in the sweat loss in resting subjects but had little or no effect on working subjects. Increasing the humidity resulted in an increase in the sweat loss at the low air speed but had little effect at the higher.

Rectal Temperature

The uniformity trial. The behaviour of the rectal temperature during the uniformity trial is summarized in Table 46. The mean value of the initial rectal temperature was 99·64(± 0·062)°F. The range was from 98·8°F to 100·3°F but, as the standard error indicates, most values were closely grouped around the mean. By the end of the third (long) rest period the rectal temperature had fallen below the initial value. The final rectal temperature was 100·22(± 0·070)°F, so that the average rise in rectal temperature was 0·58°F. The increase predicted by McArdle *et al.* (1947) for highly acclimatized subjects (see p. 60) would be 0·74°F.

The factorial experiment. Unexpected difficulties, which nevertheless should have been foreseen, arose when an attempt was made to correct the results of the factorial experiment on the basis of the results of the uniformity trial. The mean value of the initial rectal temperature in the factorial experiment was 99·15°F, which was 0·49(± 0·0456)°F less than that in the uniformity trial. This difference is to be explained on the basis of the diurnal variation in body temperature; the uniformity trial began at 1.0 p.m. and the factorial experiment at 9.0 a.m. The expected difference between the rectal temperature at 9.0 a.m. and 1.0 p.m. in Singapore (Adam *et al.* 1955) is 0·56°F, which is in reasonable agreement with the observed difference. However, as the expected difference between the two sets of experiments differs from hour to hour, the use of the results of the uniformity trial to correct the values in the factorial experiment would rest on uncertain ground.

An analysis of variance was therefore performed on the uncorrected values for the final rectal temperature in the factorial experiment. The final rectal temperature was chosen as it was to this value that the workers at the National Hospital had directed most attention. In Table 47 are set out the mean values for the significant direct effects and first order interactions. Of the direct effects only those of air temperature and work rate were significant, but these were large. Under all conditions, an increase in the air temperature produced a rise in the rectal temperature and the same was true of the rate of working.

The average effect of a change of air speed was not significant, but the interaction of air temperature and air speed was highly significant. An increase in the air speed resulted in a fall in the rectal temperature at the lower air temperature but a rise at the higher air temperature, emphasizing that at the lower air temperature there was an increase in the convective loss with increasing air speed and at the higher air temperature an increase in the convective gain. The interaction of humidity and air speed is interesting. The higher humidity produced a rise in rectal temperature at the lower air speed but was without effect at the higher speed, suggesting that the facilitation of evaporation which occurs with increasing air speed renders the difference in vapour pressure between the higher and lower humidities relatively less important.

Standing Pulse Rate

The uniformity trial. The standing pulse rate, because it was counted on all occasions, provided a more convenient measure of the effect of treatment than the sitting pulse rate. The mean values for the uniformity trial are set out in Table 48.

There was a slight downward trend, with time, in both the working and resting values, and furthermore, recovery from the effect of exercise, as measured by the pulse rate, was complete within the rest period. The rise in pulse rate produced by working was much the same for all four work periods except the first.

The factorial experiment. Analysis of variance of the corrected values of the final standing pulse rate showed that the direct effects of temperature and work rate were highly significant. The direct effect of humidity was significant at the 5 per cent level. The first order interaction of air temperature and rate of work was highly significant, and the interaction of the latter with humidity reached the 5 per cent level of significance. The interaction of air temperature and air speed also reached the 5 per cent level.

These results are summarized in the mean values set out in Table 49. It will be seen that, on the average, the effects of air temperature and work rate were large compared with that of humidity. The effect of working was much greater at the higher air temperature than at the lower, and greater at the higher humidity than at the lower.

Observed Sweat Loss and the P4SR

The correlation coefficient r_{xy}, where x is the calculated value of the P4SR and y is the mean value of the observed sweat loss of each pair of subjects, is 0·97. This agrees well with the value (0·93) found for Series I (Adam *et al.* 1952). The regression of y on x proved to be

$$Y = 2087 + 0{\cdot}9927(x - 1931).$$

The similarity between this and the corresponding equation for Series I, Section A

$$Y = 2047 + 0{\cdot}9783(x - 1968)$$

is striking. The two lines do not differ significantly either in slope or position, and both yield small positive values for the observed sweat loss when the P4SR value is zero. What was said concerning the good agreement between the observed and predicted values in Series I obviously applies equally well here but, as in Series I, there are substantial differences for certain treatment combinations.

An analysis of variance of the deviations from regression showed that the direct effects of air temperature, air speed and rate of working were all significant, as also were the interactions of air speed with air temperature and rate of working. The findings are summarized in the mean values set out in

Table 50. The most important direct effect was the difference between the values at the lower air speed and the higher. On the average, the sweat loss was less than expected at the lower air speed and more than expected at the higher air speed. On the other hand, the sweat loss at the lower dry-bulb temperature was higher than expected, whereas at the higher dry-bulb temperature it was less than expected. Resting men, on the whole, produced less sweat than expected but working men produced more. These direct effects are, however, misleading if the significant interactions are neglected. It will be seen that whereas at the higher air speed the observed sweat loss was greater than predicted at both levels of air temperature, at the lower air speed the sweat loss was much less than expected at the higher air temperature. At the lower air speed resting men produced less sweat than expected, but at the higher air speed both resting and working men produced more than expected.

Perhaps a clearer understanding of the differences between the observed and predicted sweat losses can be obtained from consideration of Fig. 10, in which a line has been drawn to represent a one to one correspondence between the observed sweat loss and the P4SR value. It is clear from this that, on the average, the observed sweat loss was greater than the expected. This was also true for the values at the lower air temperature, but at the higher air temperature there were three instances in which the observed sweat loss was less than the expected and a fourth case in which it was equal to expectation. All these four instances occurred at the lower air speed, 20 ft./min. It is probably unwise to attach too much importance to these exceptional values, but the general observation that, on the whole, the amount of sweat lost exceeds that expected does appear to be of some significance, especially as this was also found to occur in the uniformity trial. A similar observation was made in the experiments on naturally acclimatized men described in Chapter 3 (Series II) where it was concluded that the effect was due rather to the personal characteristics of the subjects (they

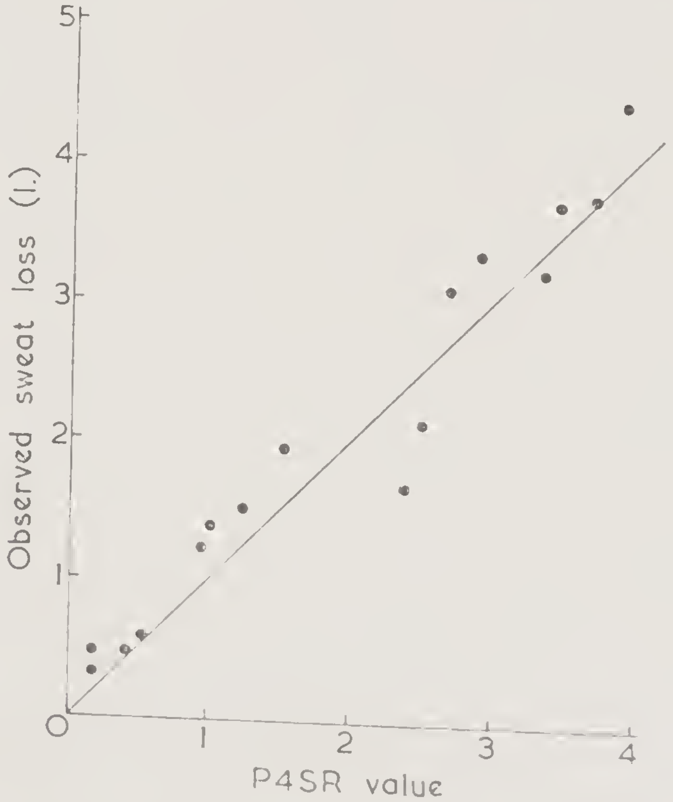

FIG. 10. Series IV. The relation between observed sweat loss and the calculated P4SR Index. The line represents ideal (1:1) correspondence.

were naturally heavy sweaters) than to their degree of acclimatization. It seems unlikely, in view of the number of subjects used and the correction that was made for personal differences, that the same explanation applies in the present case.

DISCUSSION

Comparison with Unacclimatized Men

The value of Series IV was considerably enhanced by its repetition on different subjects at Oxford, England, by Dr. J. S. Weiner and his colleagues (Hellon, Jones, Macpherson and Weiner, 1956). In the experiments at Oxford the experimental procedure at Singapore was reproduced in exact detail, and the only difference between the two series of experiments lay in the subjects used. These two groups of subjects were physically and otherwise very similar. Naval ratings were used in both cases and the similarity of the physical characteristics of the two groups is illustrated below:

	Mean value		*Standard deviation*	
	Oxford	*Singapore*	*Oxford*	*Singapore*
Age (yr)	20·17	20·92	1·84	2·19
Height (cm) ...	172·56	171·97	5·137	3·73
Weight (kg) ...	65·591	65·575	7·245	6·05
Surface area (m^2) ...	1·770	1·773	0·1154	0·09

The two groups differed, however, in that whereas the Singapore ratings had been exposed to tropical conditions for some 18 months, the Oxford group was without experience of tropical conditions.

Comparison of the results of the two uniformity trials showed that the tropical group secreted more sweat than the non-tropical group (2180 ± 40 g compared with 1699 ± 47 g), their rectal temperatures at the end of the third work period were lower (100·53°F compared with 101·45°F), and their pulse rates at the end of the fourth work period were lower (104 beats/min compared with 136 beats/min). The mean skin temperature was also lower in the tropical group and there was a difference between the groups in the response of the skin temperature to the cycle of activity. In the tropical group the skin temperature fell with work and rose on resting, in the non-tropical group it rose on working and fell with rest. Furthermore, in the tropical group the average skin temperature declined as the experiment proceeded, whereas in the non-tropical group the skin temperature tended to rise throughout the experiment. The behaviour of the rectal temperature, skin temperature and pulse rate in the two groups is contrasted in Fig. 11, 12 and 13.

The results of the factorial experiments supported the findings of the uniformity trials. In all eight experiments at the higher level of activity, and in six of the eight at the lower level, the tropical group secreted more sweat. On the whole, the effects on the sweat loss of varying the levels of the various factors were much the same in both groups, but an increase in air temperature and work rate produced a greater effect in the tropical than in the non-tropical group. The skin temperature and the pulse rate were lower in the tropical group but responded similarly in the two groups to alterations in the levels of the environmental factors. In contrast with the findings of the uniformity trials, however, there was no difference between the rectal temperatures of the two groups in the factorial experiments.

It can be said, therefore, that the tropical group secreted more sweat and exhibited smaller increases in body temperature and heart rate than the non-

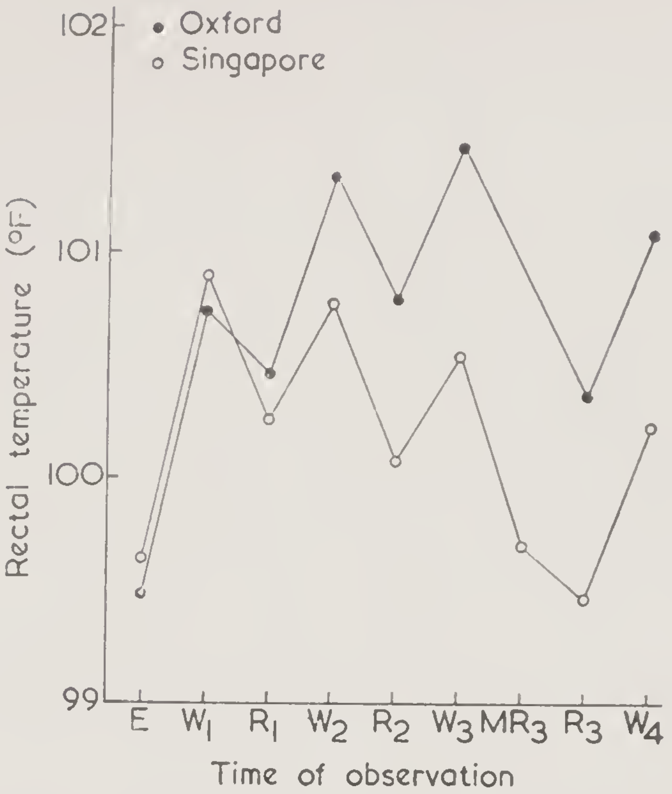

FIG. 11. Series IV. Rectal temperatures during uniformity trials at Oxford and Singapore.
E = before entry, W = end of work period, R = end of rest period, MR_3 = middle of third rest period (Singapore only).

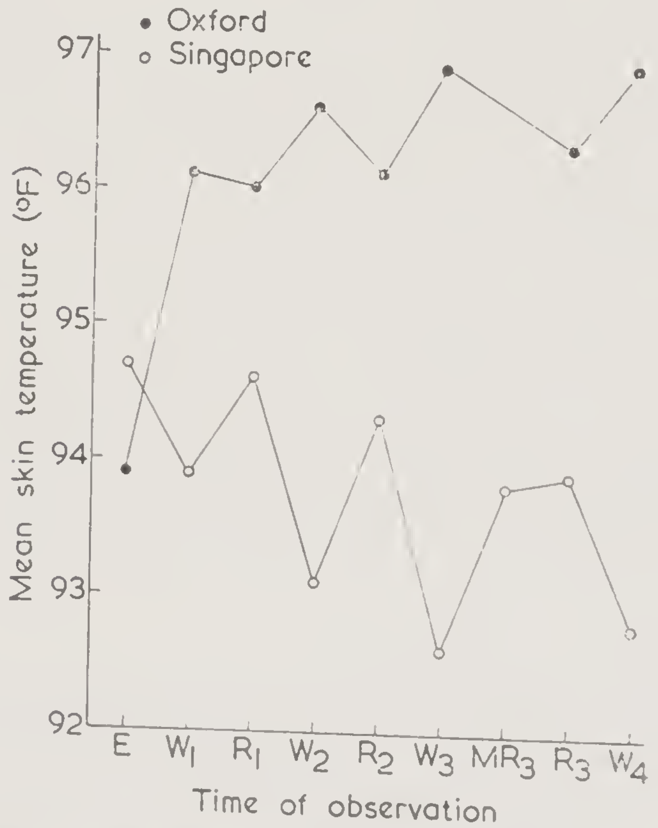

FIG. 12. Series IV. Mean skin temperatures during uniformity trials at Oxford and Singapore.
E = on entry, W = end of work period, R = end of rest period, MR_3 = middle of third rest period (Singapore only).

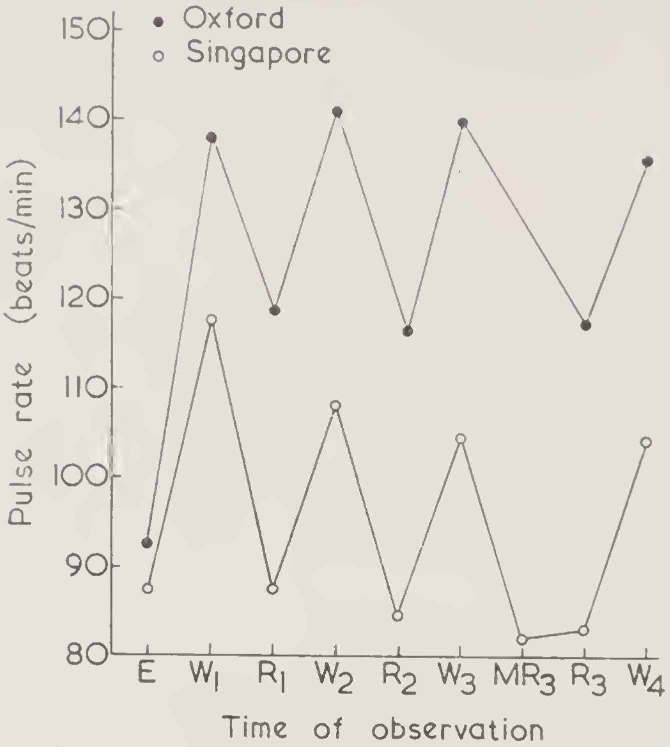

FIG. 13. Series IV. Standing pulse rates during uniformity trials at Oxford and Singapore.
E = before entry, W = end of work period, R = end of rest period, MR_3 = middle of third rest period (Singapore only).

tropical group. The effect of artificially acclimatizing subjects to hot conditions in the laboratory is to increase their ability to withstand the stress of hot environments, and this increased ability is said to be accompanied by an increase in the sweat secreted and by a diminution in the rise in body temperature and heart rate for a given set of environmental conditions. It would seem, therefore, that the naval ratings in Singapore were considerably more able to withstand the effects of heat than their counterparts in the United Kingdom who had not been exposed to tropical conditions.

A further very important conclusion which would seem to emerge from these results is that the changes accompanying natural acclimatization are identical with those that accompany artificial acclimatization, and that the identity of the two processes is thus established.

It is probable that the two groups of thirty-two subjects were representative samples, in so far as their acclimatization is concerned, of naval ratings in the two situations, and it may therefore be concluded that the Singapore subjects with whom we are concerned in the present series of experiments had acquired during their stay in Singapore a considerable degree of acclimatization to heat.

Comparison with Other Acclimatized Men

Experience gained during the conduct of the series (I, II and III) which preceded Series IV had made it abundantly clear that the naval ratings living at Singapore did not possess their maximum degree of acclimatization to heat and that exposure to higher levels of heat stress considerably enhanced their ability to tolerate hot conditions. (Further experience in Series V, VI, VII, VIII and IX, subsequently conducted at Singapore, confirmed this beyond doubt.)

The subjects used in Series III and those used in Series IV were taken from the population of naval ratings at Singapore. The former were then exposed to hot conditions until, having achieved the maximum degree of acclimatization, they exhibited a constancy of behaviour when exposed to hot conditions. It has been shown (in the previous chapter) that the behaviour of these subjects was then indistinguishable from the behaviour of the highly acclimatized subjects used at the National Hospital.

It is thus possible to recognise the following grades or degrees of acclimatization. Firstly, there is that of men without experience of tropical conditions, e.g., the Oxford subjects, who possess the lowest tolerance of heat. Exposure of such men to tropical conditions for approximately 18 months improves their tolerance of hot conditions and they exhibit the degree of acclimatization possessed by the Singapore subjects in Series IV. This represents the next level of acclimatization—that acquired 'naturally' by men living in the tropics. Exposure of such men, as in Series III, to higher levels of heat stress produces in them an increased degree of acclimatization—the third level—which appears to be identical with that exhibited by subjects used in the experiments of Dunham *et al.* (1946) at the National Hospital in London.

Sweat loss, rectal temperature and pulse rate. It is of importance, therefore, to compare the results obtained in Series IV with those obtained in the same environmental conditions at the National Hospital and in Series I, II and III at Singapore. The exact environmental conditions used in Series IV are not represented in the experiments in London, but comparison is possible between the sweat losses observed in Series IV and those predicted by the P4SR nomogram which is based on the results obtained in the experiments of Dunham *et al.* (1946). Comparison with the results of Series II is unfortunately not possible because none of the environmental conditions used in Series IV is represented in Series II, but a number of comparisons can be made with the results of Series I and III.

The comparison of the Series IV results with the results of Series I will be useful because the latter were obtained on 'naturally acclimatized' men whose degree of acclimatization appeared to alter during the course of the series as a result of their exposure to hot conditions in the laboratory. The comparison with the results of Series III will be important because Series III used a group of men similar to those used in Series IV except in that their acclimatization had been increased artificially.

These comparisons should enable conclusions to be drawn concerning the effect of acclimatization on the response of subjects as measured by their sweat loss, heart rate and body temperature. Such differences as are observed may prove to be either quantitative—in that the type of response is the same in all cases but the response differs in degree—or qualitative, in that differences exist at some combinations of environmental factors but not at others.

In Table 51 the average sweat losses in Series I, III and IV, at the environments common to those series, are set out, together with the corresponding P4SR values. At the lower dry-bulb temperature (90°F), when the wet-bulb temperature was 80°F the response in Series I and Series IV was very similar, and in both series the sweat loss was, on the whole, considerably greater than that predicted by the P4SR nomogram.

At the higher wet-bulb temperature (85°F), the results of Series I and IV were again very similar and they were again greater than the P4SR values, although not to the same extent as at the lower wet-bulb. The values in Series III were, on the whole, a little lower than those in Series I and IV and were much closer to the values predicted by the P4SR. At the lower air temperature, therefore, the behaviour of the naturally acclimatized men in Series I and IV was very similar and they appeared to produce somewhat more sweat than the highly acclimatized men of Series III and of the London experiments (as indicated by the P4SR values).

At the higher air temperature (120°F) and the lower humidity (wet-bulb 80°F) there was on the whole very little difference between the values for Series I, Series IV and the P4SR. At the higher level of humidity (wet-bulb 85°F), the mean sweat losses in Series I, Series IV and the P4SR were in agreement but exceeded the values observed in Series III.

It would appear that at the lower air temperature the P4SR, which is based on the results of highly acclimatized men, under-estimated the sweat losses of the naturally acclimatized men of Series I and IV, and, to a lesser extent, the losses of the highly acclimatized men of Series III. At the higher air temperature, the losses in Series I and IV were in agreement with the P4SR values but the losses in Series III were less than the P4SR values. This made difficult the acceptance of the simple statement that acclimatization is accompanied by an increase in sweat loss, which would imply that the P4SR values and those of Series III should exceed those for Series I and IV.

In Table 52 are set out the final rectal temperatures in the environments common to Series I, III and IV. On the whole, the results of Series I and IV were in agreement, and no certain differences could be demonstrated, either at the higher or at the lower levels of stress. At the lower air temperature, the results for Series III were very similar to the corresponding results for Series I and IV, but at the higher air temperature and the higher humidity the working subjects in Series III had markedly lower rectal temperatures than the men in Series I and IV. The latter conditions represent the highest levels of stress so that it may be said that, in so far as rectal temperature is concerned, differences between those highly acclimatized and those less so became apparent only at the highest levels of stress.

In Table 53 the pulse rates for the same environmental conditions are set out. At the lower level of air temperature the values for Series I were much above those for Series IV, but at the higher air temperature this difference tended to disappear. At the lower air temperature there was little difference between the pulse rates in Series III and Series IV, but at the highest level of stress (dry-bulb 120°F, wet-bulb 85°F) the pulse rates in Series III were considerably less than those in Series I and Series IV, and this was most marked in the case of working men. The conclusion is that, as with rectal temperature, the differences in levels of acclimatization were only readily demonstrated at the higher levels of stress.

When the three variables—sweat loss, rectal temperature and pulse rate—are considered together, the conclusion is that the pattern of response is the same for the various combinations of environmental factors examined but that the more highly acclimatized subjects have lower heart rates and lower body temperatures, although this difference is only easily demonstrable at very high levels of stress. With regard to sweat loss, although here, too, no recognisable difference in the pattern of the response can be discerned, the expected greater sweat loss in the more highly acclimatized subjects has not been demonstrated.

Upper tolerable limits. A very important piece of information concerning the level of acclimatization of the subjects used in the several series of experiments is provided by the consideration of their respective upper tolerable levels of warmth. Of the thirty-two naturally acclimatized men in Series IV who were originally chosen as subjects, three failed to complete their tests. One of these developed malaria in the interval between the uniformity trial and the factorial experiment. The remaining two both failed to complete the factorial experiment. In both cases the environment was dry-bulb 120°F, wet-bulb 85°F and air speed 300 ft./min, and both men were working subjects. (The results for these three men were discarded and another three men were substituted. In the account of the experiment the results for the three substituted men have been used throughout.)

Taken at their face value, these results indicate that 50 per cent (2 out of 4) of the men who were exposed to the most difficult conditions in this experiment, namely working in shorts at a dry-bulb temperature of 120°F, a wet-bulb temperature of 85°F and an air speed of 300 ft./min, were unable to complete the four-hourly 'Queen Square Routine'. The only general conclusion that can be drawn from such a small sample is that for some young adults naturally acclimatized to temperatures experienced in the humid tropics, but not 'artificially' acclimatized to extreme conditions of heat and humidity, this environment is likely to prove intolerable.

It is particularly instructive to compare the level at which these failures occurred with the levels at which failures occurred in the other series of experiments. In the experiments of Dunham *et al.* (1946) with artificially acclimatized subjects, one man working in shorts at an air temperature of 120°F failed to complete an experiment, but in this case the wet-bulb temperature was 88°F, the air speed 50 ft./min and the calculated P4SR Index 4·35—a level of stress considerably greater than that at which failures occurred in Series IV (dry-bulb 120°F, wet-bulb 85°F, air speed 300 ft./min and P4SR Index 3·9). In Series I one failure did occur at dry-bulb 120°F, wet-bulb 85°F and air speed 50 ft./min, but the subject concerned was wearing overalls and was known to have a lower than average heat tolerance. In Series III, whose highly acclimatized subjects are considered to be similar to those of Dunham *et al.* (1946) in their level of acclimatization, only one of the seven cases of serious heat incapacitation occurred in a man working in shorts, and this occurred at dry-bulb 120°F, wet-bulb 88°F, air speed 20 ft./min—a much higher level of stress than that in which failures occurred in Series IV. Comparison of the Series IV findings with those for Series II, set out in Table 41, is particularly instructive. In all, seventeen failures occurred in the pre-acclimatization period of the latter series. All occurred at an air temperature of 120°F and two occurred in men working in shorts at a wet-bulb temperature of 83°F. In the post-acclimatization period ten men failed, but in all cases the wet-bulb temperature was 88°F. There were no failures at dry-bulb 120°F, wet-bulb 83°F. These findings are consistent with the conception that in the first part of Series II the men had a very similar level of tolerance of hot conditions to that of the men used in Series IV, but that the subsequent period of artificial acclimatization produced an improved tolerance of heat comparable with that possessed by the subjects used in Series III. The combined results of Series II, III and IV thus provide support for the findings from Series I on the upper tolerable limits.

Water Intake and Sweating

The results of the previous series of experiments (Series III) had given rise to the suspicion that the amount of sweat produced could be seriously influenced by the water intake of the subject. It was noted in that series that, in general, the heavier sweaters tended to be the heavier drinkers and the lighter sweaters the lighter drinkers. Which was cause and which was effect was quite uncertain. It might have been thought that the heavy sweaters drank more because they were heavy sweaters, had it not been noticed that one light sweater changed his drinking habits during the course of the experiment and that as his drinking increased so did his sweating.

In order to collect more information on this subject it was decided that during the experiments in Series IV all subjects should receive exactly 1·5 l. of water administered in three doses at 50, 110 and 170 min after entering the chamber. These were the times at which the working men returned to their positions from being weighed after the first, second and third work periods. As the working men alternately worked and rested it was impossible to compare their rate of sweating before with their rate after drinking, and consequently the effect of drinking has been investigated only for the resting men.

As a working man cannot be weighed during work and must, therefore, be weighed during his resting periods, the intervals between weighings were irregular, and as the resting men followed the same schedule as the working men, their weighings also took place at the same intervals. Between the initial weighing when the subjects entered the chamber and the second weighing after the first work period 45 minutes elapsed; between this second weighing and the next weighing that preceded the second work period, 20 minutes elapsed; then 40 minutes intervened before the next weighing, and so on, with further irregularities introduced by the occurrence of a long rest period and the short final work period.

Table 54 gives the intervals between successive weighings, the times at which drinks were adminstered and the rates of sweating between successive weighings. It will be seen that for each subject there are three occasions on which the rate of sweating for a period which is not preceded by a drink (first, third and fifth) can be compared with the rate of sweating for an immediately succeeding period (second, fourth and sixth) just before which a drink was given. In addition, the rate of sweating during the seventh period, immediately before which no drink was given, can be compared with that during the eighth before which, likewise, no drink was given. As there were sixteen subjects and three drinks apiece, there are forty-eight pairs of values within each of which a comparison may be made between a period not preceded by a drink and a period which immediately follows a drink, and sixteen pairs in each of which a comparison may be made between two periods neither of which was preceded by a drink.

The results at the two dry-bulb temperatures used in the experiment were as follows; 'increase' and 'decrease' signify respectively an increase and a decrease in the rate of sweating for the second member of a pair within which comparison was made.

	D_1 (90°F)		D_2 (120°F)		$D_1 + D_2$	
	No. of Increases	*No. of Decreases*	*No. of Increases*	*No. of Decreases*	*No. of Increases*	*No. of Decreases*
No drink—drink sequences	17	7	20	4	37	11
No drink—no drink sequences	4	4	2	6	6	10

A chi-squared test on these results gave the following values (for one degree of freedom):

D_1(90°F), 1·16; D_2(120°F), 9·50; $D_1 + D_2$, 8·50.

The conclusion to be drawn is that for the experiment as a whole ($D_1 + D_2$) and for the higher dry-bulb temperature (D_2) the giving of water to drink increases the rate of sweating, whilst at the lower dry-bulb temperature the evidence is inconclusive.

It might be considered more correct to ignore the first pair of comparisons for each man. After the subjects entered the hot room there would have been some delay in the onset of sweating, and there would then have been a period during which the rate of sweating increased until some form of equilibrium with the environment was reached; the results might thus have been biased in favour of the finding quoted above. If the periods prior to and following the first drink of water are discarded, the following results are obtained.

	D_1 (90°F)		D_2 (120°F)		$D_1 + D_2$	
	No. of Increases	*No. of Decreases*	*No. of Increases*	*No. of Decreases*	*No. of Increases*	*No. of Decreases*
No drink—drink sequences	10	6	12	4	22	10
No drink—no drink sequences	4	4	2	6	6	10

A chi-squared test on these results gave the following values (for one degree of freedom):

$$D_1(90°F),\ 0{\cdot}37; \quad D_2(120°F),\ 5{\cdot}63; \quad D_1 + D_2,\ 4{\cdot}20.$$

The conclusions drawn previously still hold good although the level of significance is not so high.

It is interesting to note that the increase in sweating follows the ingestion of water at a temperature some 20°F below body temperature, the effect of which is to reduce the mean temperature of the body and thereby reduce the amount of sweat necessary for the maintenance of thermal equilibrium.

The implication of these results, viz. that the amount of sweat produced depends upon the amount of water drunk, is so important that it was considered that a more careful investigation should be carried out before any firm conclusion could be reported. This was later done during the course of Series IX and the investigation is described in Chapter 8.

Correction for Differences Between Individuals

Numerous investigators have commented on the surprising differences which have been found to exist between the reactions of individuals exposed to the same carefully controlled climatic environment. It must always be borne in mind, therefore, when attempting to compare the stress of two or more combinations of environmental factors by observing the reactions of different groups of individuals to each combination, that differences observed may be due not to the differences in climatic stress but to differences between the individuals comprising the groups.

The most obvious method of correcting for the differences between individuals when such a comparison is being made is that applied in Series IV—the use of a uniformity trial in which all the subjects are treated alike and the subsequent use of the technique of analysis of covariance to correct the values in the factorial experiment. The objection to this is that the use of a uniformity trial not only doubles the experimental time required but, as already noted, is likely to affect the acclimatization of the subjects. It is profitable, therefore, to enquire whether it is possible to identify the most important sources of the differences between men and thus render a uniformity trial unnecessary.

Examination of the results of Series IV failed to identify any characteristic in the subjects which could be associated with variations in rectal temperature and pulse rate, but sweat loss was found to be clearly associated with body size.

The source of the differences between individual sweat losses. If the uniformity trial is treated as a dummy experiment and the results for each individual in the uniformity trial are ascribed to the treatment which he experienced in the factorial experiment (cf. Tables 43 and 44), an analysis of variance can be performed as if the results were those of a real experiment.

This procedure was followed and the findings are set out in Table 55. As all the subjects were treated alike, any significant differences must clearly be due to differences existing between the subjects. The value for 'W' is highly significant. This means that the subjects who later were treated in the factorial experiment at the lower level of wet-bulb temperature reacted to a given set of conditions in a way which differed from that in which the subjects who were later treated in the factorial experiment at the higher level of wet-bulb temperature reacted to the same conditions. If the physical characteristics of the two groups are examined it is found that, although the subjects were allotted at random to the various treatments in the factorial experiment, it happened by chance that the lighter men were allotted to W_1 and the heavier men to W_2. Further, it appears that those who were heavier in weight were also heavier sweaters, as can be seen from Table 56, which suggests that sweating is proportional to body weight.

Examination of the relation between sweat loss and body weight in the uniformity trials, assuming the relation to be linear, gives a correlation coefficient r of 0·76 which is significant at the 0·1 per cent level. The corresponding regression equation is

$$Y = 2183 + 0{\cdot}0285\,(x - 65576)$$

where x is the body weight (g) and y is the sweat loss (g). The relation clearly can hold only over a limited range, for the equation indicates some loss of sweat when the body weight is zero.

Numerous workers have suggested that sweat loss is proportional to surface area. As the surface area of the body, like its mass, is a function of its linear dimensions, it might be thought, therefore, that the relation between weight and sweat loss was merely an expression of the relation between mass and surface area, and that the correction of sweat loss on the basis of surface area might be more satisfactory.

The relation between the sweat loss in the uniformity trial and the surface area was examined and the correlation coefficient (r) was found to be 0·65, which is also significant at the 0·1 per cent level. The corresponding regression equation is

$$Y = 2183 + 1677\,(a - 1{\cdot}773)$$

where y is the sweat loss (g) and a the surface area (m^2). Comparison of this relation with the relation between sweat loss and body weight would suggest that, in fact, body weight is a rather better basis of correction than surface area.

It has been pointed out by Quiring (1944) that one of the earliest determinations of the surface area of the body established the formula

$$\text{Surface area} = K(\text{Weight})^{2/3}$$

which was apparently arrived at merely by consideration of the dimensions of area and volume. It is later shown that K (often called the Meeh constant) was about 10 for most mammals.

Let us suppose that sweat loss (y) and weight (x) are related according to the equation

$$y = Kx^b.$$

If the sweat loss is proportional to body weight, then b will be equal to unity. If, on the other hand, sweat loss is proportional to surface area, then b will equal 2/3 (0·667).

Taking logarithms of both sides of the equation we have

$$\log y = \log K + b \log x.$$

If we examine the relation between log sweat loss and log weight in the results of the uniformity trial, there is a highly significant correlation ($r = 0{\cdot}77$) and the regression equation is

$$\log Y = 3{\cdot}336 + 0{\cdot}878 (\log x - 1{\cdot}815)$$

so that b is seen to have the value 0·878 which is closer to 1·000 than to 0·667. This would support the view that weight is somewhat better than surface area as a basis for correction.

The individual values for the total sweat loss in the uniformity trial, together with the values for sweat loss per kilogram of body weight and per square metre of surface area, are set out in Table 43. Both methods of expression reduce the differences between individuals, but the loss per kilogram appears to be a somewhat more satisfactory measure than the loss per square metre.

If, when the sweat losses in the factorial experiment are expressed as grams per kilogram of body weight (Table 44), we use as a measure of the effectiveness of the correction the reduction in the differences in the sweat loss between pairs of subjects treated alike, the results are disappointing. It is true that in some cases, notably with working subjects, the correction on the basis of body weight served to reduce the differences between individuals but in others, chiefly with resting subjects, it is obviously inferior to the correction on the basis of surface area. It is clear, then, that the conclusions which applied in the case of the uniformity trial do not apply in the case of the factorial experiment and it is necessary to enquire into the reason.

The regression equations expressing the relation of sweat loss to body weight and to surface area in the general form $y = a + bx$ are unsatisfactory physiologically, as the empirical constant b is without clear physiological significance (Kleiber, 1950). A more reasonable approach would be the indirect one of considering what form the equation connecting body size and sweat loss might be expected to assume.

If it is postulated that the sweat loss of the body is proportional to the requirements for evaporative heat loss, the position becomes much clearer. The amount of sweat required will depend upon the convective and radiant heat gain from the environment (which may be either positive or negative), and the heat produced by the metabolic activity of the body. This energy expenditure may be divided into two parts, a basic fraction representing the cost of sitting and a fraction representing the cost of additional activity.

In the case of men sitting, lightly clad, in a hot environment, the convective and radiant heat gain from the environment will take place through the surface of the body and will be clearly proportional to the surface area—that is to say, proportional to $W^{2/3}$ where W is the body weight. If the metabolic rate of sitting is proportional to the surface area, then we may consider the heat production of the body in these circumstances to be also proportional to $W^{2/3}$. Galvão (1948*a*, *b*) found that in the tropics the basal metabolism is proportional not to the surface area but to something between $W^{0 \cdot 78}$ and $W^{0 \cdot 88}$ depending upon the stature, and Cullumbine (1950) found that the metabolism for Sinhalese subjects is proportional to $W^{0 \cdot 79}$. Whether these findings are accepted or not, it should be observed that the values are at least as close to $W^{0 \cdot 67}$ as to $W^{1 \cdot 0}$. It is to be expected, therefore, that for sitting subjects the sweat output would be proportional to W^{x} where x is not greatly different from 0·67. In other words, it would be roughly proportional to the surface area, even if in practice the surface area is calculated from an empirical formula such as that of DuBois.

In the case of working men, the radiant and the convective exchange with the environment will be proportional to $W^{2/3}$, as in the case of sitting men. The metabolic heat will depend upon the rate of work. In the case of working men following the 'Queen Square Routine' (as in the uniformity trial), to the basic amount expended in resting must be added that amount expended in step-climbing. As step-climbing involves raising the weight of the body through a constant distance, the latter amount is proportional to the first power of the weight ($W^{1 \cdot 0}$). The final result will depend upon the relative magnitudes of the various factors concerned. If the convective and radiant heat exchanges with the environment are small—that is, if the temperature of the skin is very close to that of the environment, as was the case in the uniformity trial—then we may expect the sweat loss to be proportional to some power of W greater than 0·67 but less than 1·0. The value of 0·88 that was obtained seems to be very reasonable.

The uniformity trial is, therefore, seen to have been a special case, and the general application of the conclusions could be extremely misleading. The question that now arises is whether correction of the sweat loss for body size is desirable and, if so, what method should be used. The answer to the first part is clearly in the affirmative. There is no doubt that the amount of sweat produced under any given set of conditions does depend on the size of the body. In the group of men who performed the uniformity trial the variation was not great and spectacular results from correction for body size could not be expected. Subject 25 was by far the heaviest, with a weight of 86 kg, and his sweat production was far greater than that of anyone else, but when expressed per kg of body weight it fits in well with the other values. With a non-homogeneous group, or with two groups of widely different size, such as children and adults or racial groups that differ greatly in size, correction becomes important.

What basis should be used for correction depends, as has been indicated, on the conditions. There are certain practical advantages in the use of loss per kilogram rather than a more complicated function of weight or of weight and height. Loss per kilogram is easily applied and readily comprehended and, in those cases in which the energy expended is proportional to the weight, as for example in step-climbing, its use will give greater accuracy than the use of surface area.

If it is accepted that the amount of sweat produced by a man in a given environment depends upon his body size, this should be taken into consideration when an attempt is made to predict his sweat loss. Similarly, if it is intended to use sweat loss as a measure of the stress of the environment, it must be stated as a function of body size. Hence, the predicted four-hourly sweat loss should be expressed per unit surface area or per unit body weight. This would have the advantage of increasing the accuracy of the prediction for individuals if, as McArdle *et al.* (1947) suggest, the P4SR is used for the prediction of the bodily requirements of salt and water for a given environment—a practical use of the P4SR which might be of considerable importance.

Experience has shown that, even under the most carefully standardized conditions of environment, fluid intake and work rate, there is a residuum of variation between individuals in sweat output which bears no relation to body size. There are men who appear to secrete less sweat than most, but more often are found those whose sweat secretion is far in excess of that of their fellows. These personal sweating characteristics are very constant and in a group of acclimatized men under standardized conditions the differences between individuals remain remarkably constant.

SUMMARY

1. The purpose of Series IV was to compare the physiological responses to warm environments of men naturally acclimatized by living in the tropics with those of men artificially maximally acclimatized, and to determine the degree of acclimatization of one group relative to that of the other.

2. Thirty-two volunteers were chosen from men serving in H.M. ships in Singapore. In order not to disturb their natural degree of acclimatization they were exposed to hot conditions on only two occasions separated by an interval of 3 days.

3. On the first occasion they were all treated alike in a uniformity trial in which they performed the standard 'Queen Square' step-climbing routine at dry-bulb 100°F, wet-bulb 85°F and air speed 100 ft./min. On the second occasion each of the sixteen pairs was allocated to one of the sixteen combinations of dry-bulb temperatures 90°F and 120°F, wet-bulb temperatures 80°F and 85°F, air speeds 20 ft./min and 300 ft./min, working (step-climbing as before) and resting. The results of the first experiments were used to correct for differences between subjects in the second by the method of analysis of covariance.

4. The sweat losses in the factorial experiment were compared with those predicted by the P4SR nomogram (which is based on results obtained on highly acclimatized men in London), with those of Series I (naturally acclimatized men) and with those of Series III (highly acclimatized men). At the lower air temperature, the sweat losses in Series I and Series IV exceeded those predicted by the P4SR nomogram and those of Series III. At the higher air temperature there was, on the whole, little difference between the sweat losses of Series I, the sweat losses of Series IV and the P4SR values, but all three were greater than the sweat losses observed in Series III.

5. The pulse rates and rectal temperatures observed in Series I, III and IV were also compared. When the three variables, sweat loss, rectal temperature and pulse rate were considered together, it was clear that although the pattern of the response in all three series was the same for the various combinations of environmental factors examined, at the higher levels of stress the more highly acclimatized subjects of Series III had lower heart rates and body temperatures. The expected higher rate of sweating in the more acclimatized subjects of Series III was, however, not demonstrated.

6. Repetition of this series of experiments in England showed that the naturally acclimatized subjects in Singapore were considerably more able to withstand hot

environments than the unacclimatized subjects in England. Comparison of the results of these two series of experiments also served to establish that the physiological changes accompanying artificial acclimatization were identical with those accompanying natural acclimatization.

7. It was concluded that the degree of acclimatization of the subjects used in Series IV lay between that of unacclimatized men in England and that of the highly acclimatized subjects used in Series III which is similar to that of the subjects used in London.

8. During the course of Series IV it was observed that the drinking of cold water was followed by an increased output of sweat.

9. The variation occurring in the amount of sweat secreted by individuals when treated alike was examined and it was concluded that this variation could be reduced, but not entirely removed, by correcting the sweat output for the body weight or the surface area. Body weight provided a somewhat better basis of correction for working subjects.

CHAPTER 6. THE CONTRIBUTION OF RADIANT HEAT TO ENVIRONMENTAL STRESS

An account of the work of Helen M. Ferres, R. H. Fox, J. W. Jack, R. T. John, A. R. Lind, R. K. Macpherson and P. S. B. Newling

The thermal exchange between the body and its environment may conveniently be divided into three parts due, respectively, to convection, evaporation and radiation. In the experiments described in previous chapters the thermal exchange by radiation between the body and its surroundings had been standardized by ensuring that the temperature of the walls of the climatic chamber was maintained at the temperature of the circulating air. In these experiments heat exchange by radiation would have varied with the air temperature, but would have remained approximately constant for any particular air temperature, and hence temperature of the surroundings. It could only have been approximately constant because the thermal exchange by radiation depends on the temperature of the surface of the body as well as the mean radiant temperature* of the surroundings, and changes in the humidity and air speed of the environment would be reflected by changes, although small, in the skin temperatures of the body.

In practice, however, the temperature of the surroundings may be very different from that of the air. In lightly constructed buildings in cold weather one finds that the temperature of the surroundings is below that of the air, but in many situations, especially in ships and factories, where excessive heat is a problem, the mean radiant temperature is above the air temperature. Assessing the environmental stress under such conditions in terms only of air temperature, humidity and air speed would give very misleading results, since to the thermal stress thus calculated there must be added a very considerable heat load representing heat gain by radiation from the hot surfaces.

In ships, high levels of radiant heat occur not only in boiler rooms and machinery spaces but also in such places as galleys and radar rooms. Even on the mess decks, the deck, deck head and bulkheads may be heated by contiguous machinery, steam pipes or the sun, so that the temperature of their surfaces is above that of the circulating air. It is therefore important that some means should be devised for taking into account the temperatures of the surrounding walls when assessing the heat stress of these environments.

Such investigations require a device by means of which the temperature of the surrounding walls may be varied at will and, at the same time, the temperature and humidity of the enclosed air maintained at the desired levels. This need was fulfilled by the design of a radiant-heat tunnel by the Heat Radiation Panel of the Climatic Efficiency Subcommittee of the Royal Naval Personnel Research Committee. It was built at H.M. Dockyard, Chatham, and installed in the Royal Naval Tropical Research Unit towards the end of 1950.

In order to obtain controlled conditions of air temperature, humidity and air speed within the tunnel, it was erected in a test section of the main climatic chamber which has been described in Chapter 1. To accommodate the tunnel in this chamber certain structural alterations were necessary. The observation chamber was decreased in size, one set of honey-comb air vanes was removed and the direction of the air flow was reversed so that the air was drawn through the tunnel.

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* The *mean radiant temperature* at any point may be defined as that temperature at which the surroundings would have to be in order to produce at the point of observation the intensity of radiation observed, if they were at a uniform temperature and behaved as ideal black surfaces.

The tunnel, as first installed, was provided with switch-gear that enabled the power supplied to be varied in a series of eight steps. Preliminary trials of the tunnel soon after its installation showed that this arrangement would require some modification. The lowest level (20 per cent) produced panel temperatures 45–50°F (according to the air temperature and air speed) above air temperature. Such a value was clearly too high for use as the lowest level of radiant heat in physiological experiments, so that some modification of the switch-gear was required in order to permit lower levels of power input to be used. In addition, to allow the temperature of the walls to be adjusted to any chosen value, and maintained there, some further modification was necessary. These modifications were subsequently effected by means of the installation of additional switch-gear designed and built by H.M. Dockyard, Chatham. This modified switch-gear proved entirely satisfactory and enabled the walls, the roof and the floor to be maintained at any temperature chosen from a very wide range, with their mean value accurate to within 1°F.

As time was limited, it was decided to devote the interval necessary for the delivery of the new switch-gear to the examination of the effect of the use of the radiant-heat tunnel, as installed, on the range of controlled conditions (air temperature, humidity and air speed) available for experimentation within the climatic chamber—followed by a brief preliminary investigation of the effect of radiant heat on naturally acclimatized young men in preparation for the large-scale factorial experiment on the physiological effects of added radiant heat which had already been planned. This pilot experiment was Series V—the fifth of the series of investigations conducted at the Tropical Research Unit.

After the installation of the modified switch-gear, the large scale investigation, Series VI, was conducted. At its conclusion, considerable progress having been made in the problem of the measurement of mean radiant temperature by the use of metal model men, it was considered that a further investigation to explore the effects of added radiant heat at higher levels was necessary, and a further series of experiments (Series VII) was conducted. The results of all three series were reported together by Ferres, Fox, Jack, *et al.* (1954).

AIMS OF THE INVESTIGATIONS

The aims of all three series may be stated, in formal terms, as follows:

1. To assess, in terms of rate of sweat loss, elevation of body temperature, increase in pulse rate and changes in skin temperature, the effect of increasing the mean radiant temperature, at different levels of air temperature, humidity, air speed and clothing, on young men working according to the four-hourly 'Queen Square Routine'.
2. To continue the critical examination of the P4SR nomogram, particularly with respect to the use of the globe-thermometer reading as a means of correcting for an increased mean radiant temperature in the prediction of the four-hourly sweat loss.
3. To assess the extent to which the Effective Temperature Scale can be regarded as a scale of environmental stress and, more particularly, the

adequacy of the correction proposed by Bedford (1946) to the scale to allow for the effects of added radiant heat.

4. To assess the effect of increasing the mean radiant temperature on the upper tolerable and desirable levels of temperature and humidity.

In addition to these general aims, Series V and Series VII had aims peculiar to themselves. Series V was a pilot experiment conducted to prepare the way for Series VI. Its purpose was to gain familiarity with the operation of the apparatus used, to determine suitable values for the levels of the several factors in Series VI and, as it was both convenient and expedient to use naturally acclimatized men, to gather information on such men to supplement the findings in Series IV, recently concluded. Series VI was the main and most complete experiment, and on its results the findings set out in this account chiefly depend. Series VII was intended to provide additional information beyond that provided by Series VI, and to clarify certain points. Its special aims were: to investigate the effect of levels of radiant heat higher than those employed in Series VI; to fill what was considered to be an unduly large gap between the two dry-bulb temperatures (90 F and 110°F) employed in Series VI; and to obtain more precise information on the effects of clothing, as in Series VI certain comparisons between shorts and overalls were confounded with differences between subjects. In both Series VI and Series VII artificially acclimatized men were used as subjects.

THE RADIANT-HEAT TUNNEL

The preliminary investigation of the characteristics of the radiant-heat tunnel has strictly no place in a study of the physiological effects of radiant heat, but it is necessary to give some account of the findings because they so largely affected the range of conditions explored in the physiological investigations. The range of conditions used was, of course, limited by the conditions that could be obtained when the tunnel was in operation, just as the number of subjects which could be used was limited by the physical dimensions of the tunnel.

The construction of the radiant-heat tunnel has been described in full by Smith, Underwood, Hickman and Griffiths (1949). Briefly, it consisted essentially of a rectangular tunnel, or box open at both ends, 10 ft. 10 in. (330 cm.) long, 8 ft. 8 in. (264 cm.) high and 6 ft. 6 in. (198 cm.) wide. The roof, floor and two sides were made up of a number of rectangular panels each 2 ft. 2 in. (66 cm.) square, carried in a steel frame. Within the panels were electrical heating elements, and the radiating (inner) surfaces were painted matt black so that their emissivities for the temperatures used were close to unity. Attached to the radiating surface of each panel was a nichrome-eureka thermocouple which, by the use of appropriate switches, enabled the temperature of the surface of each panel to be measured.

As the tunnel was an open-ended box, the mean radiant temperature of a point within it depended not only on the temperature of the heated panels but also on the temperature of the walls and any other surfaces in the climatic chamber that were 'visible' from the point in question. The temperature of these surfaces could be determined by measurement, or assumed to be (as was found to be the case when measured) at air temperature. The average temperature of the roof, floor and sides of the tunnel could be calculated from the values for the individual panels as measured by the thermocouples attached. From this information and from a knowledge of the solid angles subtended by the heated panels and by the unheated walls, and their respective emissivities, the mean radiant temperature at any point could be calculated.

This, however, would be a laborious process and the results when obtained probably questionable. Other methods of measuring mean radiant temperature were required, and their development and use form the subject of a separate paper by Newling (1954). By the use of metal model men, he was able to determine the mean radiant temperature at the site in the tunnel occupied by the subjects in these experiments, and to show that this value could be correctly determined from the readings of globe thermometers suspended in the position which would normally be occupied by the subjects.

The investigation of the behaviour of the tunnel over a wide range of air speeds and levels of radiant heat would have been a time-consuming business. Most attention, therefore, was given to investigating at length what were considered to be the most 'difficult' conditions likely to be commonly encountered—the combination of low air speed and a moderate level of radiant heat. The behaviour of the tunnel under other conditions was checked by spot tests to confirm that it did indeed behave as expected. Later investigations using the modified switch-gear in general confirmed the findings. In one respect, however, a mistake was made; the magnitude of the effect of increasing the air speed on the temperature of the surface of the panels was, at first, seriously under-estimated, as became apparent when Series V was performed.

The essential effect of operating the radiant-heat tunnel was to introduce into the climatic chamber a source of heat from which heat was transferred to the air in the chamber at a rate which depended upon the temperature of the panels and the speed of the air. This resulted (since the refrigeration capacity of the air-conditioning plant remained unchanged) in a restriction in the range of controlled conditions which could be maintained within the chamber.

The effect on the range of air temperatures available was to raise the value of the lowest air temperature which could be maintained in the chamber. This effect was of no significance as the minimum temperature obtainable, even at high levels of radiant heat and high air speeds, was well below that required for experimental purposes.

The effect on the range of humidity was more important. As the dew point of the air was controlled by cooling a part of the circulating air and the amount of refrigeration available remained unchanged, the value of the lowest wet-bulb temperature obtainable at a given dry-bulb temperature was raised. Since there was no method of adding moisture to the air within the chamber, the heating of the air by the radiant-heat tunnel reduced the degree of saturation of the air in the tunnel and thus reduced the value of the highest wet-bulb temperature that could be obtained at a given dry-bulb temperature.

Perhaps the outstanding effect of operating the radiant-heat tunnel was the restriction imposed upon the minimum air speed which could be used, with control of the air temperature still maintained. Even at moderate levels of radiant heat, when the air speed was below 100 ft./min the difference between the air temperature at the front and at the rear of the tunnel was excessive, irregularities occurred in the temperature from place to place in the tunnel, and strong convection currents were present. It was found subsequently that a much more satisfactory control of air temperature was possible at an air speed of 150 ft./min and this was adopted as the lowest level of air speed to be used in later experiments. This restriction was very serious, as the change in the physiological effect of air speed over the range 0–100 ft./min is very great.

The effect of increasing the air speed on the temperature of the panels was recognised very early, but its true magnitude was not appreciated until Series V was completed. In this series of experiments, keeping the power input constant at 25W/ft.^{2} and increasing the air speed from 100 to 350 ft./min reduced the mean panel temperature by 12°F.

Fig. 14 illustrates diagrammatically the effects described, at air speed 150 ft./min and 20 per cent power input (25W/ft.^{2}). (The effect of increasing the air speed, or increasing the level of radiant heat, is to lower still further the maximum wet-bulb for a given dry-bulb.)

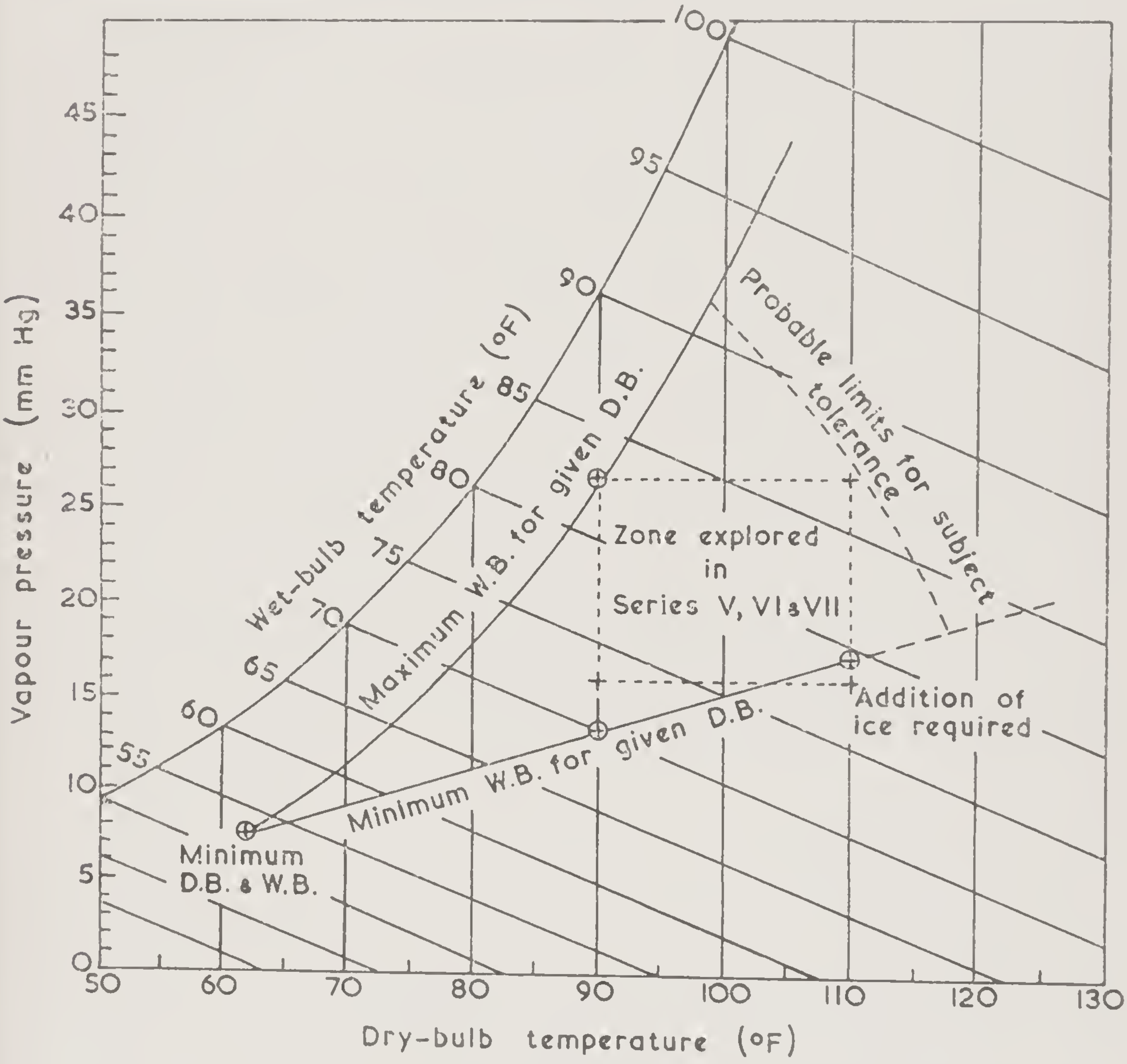

FIG. 14. The restrictions imposed on the range of air temperature and humidity available for experimental purposes in the climatic chamber by the use of the radiant heat tunnel at 20 per cent power input (25W/ft.^{2}) with air speed 150 ft./min.

Yet another limit to the experimental zone was set by the tolerance of the subjects. Experience gained in previous experiments of the levels at which collapse occurred provided a reasonable body of information from which to deduce the probable position of the line drawn in Fig. 14, although before Series V and subsequent experiments there was no information on which to base the effect on its position of varying the level of radiant heat. The line, as shown, is intended to indicate the position for naturally acclimatized men in the tropics performing the four-hourly 'Queen Square Routine', working in shorts.

A higher degree of acclimatization would shift the line to the right, as would a lower level of energy expenditure, e.g., sitting at rest. A lower level of acclimatization or the wearing of heavier clothing would tend to shift the line to the left. The occurrence of two cases of incipient collapse during Series V, at dry-bulb 110°F, wet-bulb 87·5°F, air speed 100 ft./min and a mean radiant temperature of 129°F, confirmed that the line shown was a reasonable estimate.

Series V: Preliminary Physiological Investigation

The special purposes of this series of experiments, viz., to gain familiarity with the operation of the radiant-heat tunnel and the associated apparatus, and to determine suitable values for the levels of the several factors in Series VI, have already been referred to (p. 97). It must be stressed, however, that this was a pilot investigation, with the limitations and short-comings inseparable from this type of investigation. It was essentially a case of learning by doing. The most unsatisfactory feature of this series of experiments was that limitations on the time available for experimentation required the investigation to be conducted in the interval between the installation of the tunnel and the installation of the additional switch-gear necessary for accurate control of panel temperature.

The chief purpose of the investigation, from the physiological point of view, was to obtain an estimate of the magnitude of the effect of added radiant heat at different levels of air temperature, humidity and air speed. It was not directly concerned with the main effects of air temperature, humidity and air speed as these were relatively well known, having been the subject of investigation in previous experiments.

The chief reason for the use of naturally acclimatized men was that delay for the process of artificial acclimatization was thereby avoided. In addition, the use of these subjects extended the information gained on the behaviour of such men in the recently completed Series IV.

METHODS

Experimental Design

The experimental design adopted was a factorial experiment involving the following factors:

Dry-bulb temperature at two levels, D_1 and D_2;
Absolute humidity at two levels, H_1 and H_2;
Air speed at two levels, A_1 and A_2;
Added radiant heat at two levels, R_1 and R_2.

Only one work-clothing combination, 'shorts working', was used. There were sixteen subjects, $S_1 - S_{16}$, arranged in eight pairs. The climate combinations were allotted so that comparisons between R_1 and R_2 at any given temperature, humidity and air speed, were based on the results of the same pair of subjects.

Environmental Conditions

The levels of air temperature (90°F and 110°F) and humidity (16·5 mm Hg and 27·0 mm Hg) chosen define the area marked out in Fig. 14, and were considered to provide the largest suitable range of conditions, as determined by the limitations imposed by the equipment on the one hand and the tolerance of the subjects on the other, that could be investigated.

In previous experiments (Series I–IV) involving the investigation of the effects of air temperature at various levels of humidity, the humidity factor had always been represented by the wet-bulb temperature. For example, experiments had been conducted at dry-bulb temperatures of 90°F and 120°F and wet-bulb temperatures of 80°F and 88°F, so that the four conditions investigated were dry-bulb 90°F/wet-bulb 80°F, dry-bulb 90°F/wet-bulb 88°F, dry-bulb 120°F/wet-bulb 80°F and dry-bulb 120°F/wet-bulb 88°F. In this series of experiments however, absolute humidity expressed in terms of the partial pressure of water vapour in the atmosphere was used to define the level of humidity.

The amount of water evaporated from a surface per unit time, if the air speed is neglected, is a function of the difference between the vapour pressure on the surface of the liquid and the vapour pressure in the ambient atmosphere. Therefore, in a factorial experiment in which humidity is one of the factors, the variable of which the level must be kept constant is not the wet-bulb temperature but the vapour pressure in the atmosphere, because the latter is the physical quantity which controls the rate of evaporation. In the examples quoted above, the vapour pressure of water in the air at dry-bulb 90°F/wet-bulb 80°F is 23·5 mm Hg; at dry-bulb 120°F/wet-bulb 80°F it is 14·5 mm Hg; at dry-bulb 90°F/wet-bulb 88°F it is 33·5 mm Hg and at dry-bulb 120°F/wet-bulb 88°F it is 25 mm Hg. Thus, although the wet-bulb has been maintained constant, the physical property of ambient air which controls the rate of evaporation has been allowed to vary widely. This fact has, of course, been recognized by many other workers, and the use of absolute humidity rather than wet-bulb temperature is now commonly adopted.

For this reason, it was decided that a break should be made with previous practice and the use of the wet-bulb temperature to define the level of humidity abandoned. Series V, as a pilot experiment, was considered to provide a suitable occasion. It was found that it was beyond the refrigeration capacity of the plant to produce the chosen lower level of humidity (16·5 mm Hg) at the higher air temperature (110°F) but this difficulty was overcome, as shown in Fig. 14, by the addition of ice to the circulating cold water supply used for dehydrating the air.

The two levels of air speed chosen were A_1 (the lower). 100 ft./min and A_2 (the upper), 350 ft./min.

The choice of the levels of added radiant heat was the most difficult, owing to the inadequacy of the existing switching arrangements for the control of the temperature of the panels. The levels decided upon were zero (i.e., with the wall of the tunnel at air temperature) for the lower level, R_1, and for the higher level, R_2, the 20 per cent level of power input (25W/ft.^{2}).

The levels of the various factors used are summarized below:

Factor	*Lower level*	*Upper level*
D (air temperature)	D_1, 90°F	D_2, 110°F
H (humidity: water-vapour pressure)	H_1, 16·5 mm Hg	H_2, 27·0 mm Hg
A (air speed)	A_1, 100 ft./min	A_2, 350 ft./min
R (added radiant heat)	R_1, nil—walls at air temperature	R_2, switches at '20

The wet-bulb temperature corresponding to a water-vapour pressure of 16·5 mm Hg at 90°F (32·3°C) is 73°F (22·8°C), and at 110°F (43·3°C) is 78·5°F (25·8°C). The wet-bulb temperature corresponding to 27·0 mm Hg at 90°F is 83°F (28·3°C), and at 110°F is 87·5°F (30·8°C).

Subjects

In this series, and the succeeding series of experiments, the volunteers from the Royal Navy previously used as subjects were replaced by volunteers from Army units serving in Malaya and Singapore. They were very similar in age, build and length of tropical service to the naval subjects previously used and proved equally satisfactory as experimental subjects. There is no reason to believe that the results obtained from one group would not apply equally well to the other.

Allocation of Treatments

In allocating the treatments it was desired to achieve the following ends: first, that the treatments should be allotted to the subjects at random; secondly, that comparisons between the two levels of radiation should involve the same subjects and, thirdly, that no treatment should be affected by a previous treatment. The procedure adopted was as follows.

All allocations of treatments were made by lot. First, to each of the eight pairs was allocated a pair of treatments, identical with respect to D, H and A, and with R at both R_1 and R_2. Four pairs were allocated to be exposed to R_1 first and four to R_2 first. When these allocations had been made, four of the eight treatments which had been chosen as first treatments were allotted at random to days 1 to 4. Days 5 to 8 were then fixed as the days on which the second members of these four pairs of treatments should be given, and these were allocated in order so that exactly 4 days intervened for each pair of subjects between their first and second experiments. Similarly, days 9 to 12 were allocated to the remaining four 'first' treatments and days 13 to 16 to the second member of each pair of experiments, again observing the four-day interval between exposures for each subject.

Experimental Procedure

During the 4 hr spent in the climatic chamber the subjects sat at rest on wooden stools 12 in. high or 'step-climbed' on the same stools 12 times per min according to the usual 'Queen Square Routine' for working men. Sweat losses, skin and rectal temperatures, and heart rate were measured as in Series IV (p. 77). The fluid intake was again standardized at 1·5 l. of water, 500 ml. being administered to each subject 50, 110 and 170 minutes after entering the hot room.

Control of Environmental Conditions

Air temperatures were measured at the centre of the inlet and of the outlet of the tunnel every 5 min. When there was a difference between these values, conditions were adjusted so that the mean of the two readings was the desired temperature. It was assumed that the mean of the temperatures at the inlet and outlet would represent the air temperature at the centre of the tunnel where the subjects worked.

Complete sets of panel temperatures were taken at the beginning, in the middle and at the end of the experiment. Globe thermometers were set up at the front and rear of the tunnel at diagonally opposite corners and were read at 5-minute intervals, but it was appreciated that these would give little indication of the mean radiant temperature in the space occupied by the subjects. At the conclusion of the experiment, therefore, two globe thermometers were set up in the space occupied by each of the two subjects at heights of 2 and 4 ft. from the floor and the environmental conditions maintained until the globe thermometers came to equilibrium. There was some variation between the temperatures of the globe thermometers so placed and in the air speeds over them, so the values derived for the mean radiant temperature were converted to a single figure by the not very satisfactory expedient of averaging.

RESULTS

Environmental Conditions Achieved

It was realised before the series was begun that, in the experiments involving added radiant heat, for a given input of electrical energy variations in the air speed would cause variations in the panel temperature. An increased air speed would result in increased convective heat loss from the panels and, consequently, a drop in panel temperature, and thereby a lowering of the mean radiant temperature of the surroundings. But it was thought that this change would not be large compared with random changes in temperature which might occur with a given switch setting (as there was no accurate means of controlling the panel temperature). However, when the experiment was embarked on it was soon found that the change in panel temperature with change of air speed was large and could not be neglected.

To adjust the panel temperatures so that they were the same at the lower air speed (A_1) as at the higher (A_2) required either that the temperature at A_1 should be reduced or that the temperature at A_2 should be increased. The first alternative was impossible, as the lowest level of heating was in use. The second alternative, i.e., increasing the level of radiant heat at A_2, appeared to be unsatisfactory as the next level available gave a value which was too high and which, furthermore, made it difficult to achieve the conditions of dry-bulb 90°F/wet-bulb 83°F (D_1H_2) and dry-bulb 110°F/wet-bulb 78·5°F (D_2H_1) (Fig. 14). It was decided, therefore, to proceed with the experiment as planned and to treat the results for the purposes of analysis as two experiments conducted at air speeds of 100 ft./min (A_1) and 350 ft./min (A_2) respectively in which the level of R_2 at A_2 was less than the level of R_2 at A_1. This course has been adopted throughout in the presentation of the results.

When the mean radiant temperature at the position occupied by the subjects was calculated from the measured temperature of the panels, it was found that under all conditions in which added radiant heat was used the values obtained exceeded the dry-bulb temperatures by approximately twice the values for this excess obtained from the globe-thermometer readings according to the method of Bedford (1946). Although it was suspected that the difference was due to an error in the formula used for calculating the mean radiant temperature from the panel temperature, it was not known for certain whether this was so. In fact, this uncertainty continued even after the performance of Series VI until the work of Newling (1954) showed that the mean radiant temperature derived from the globe-thermometer readings was correct. The discrepancy between that value and the value calculated from the panel temperature was due to a failure to take into account a number of factors, such as the screening effect of the metal false floor of the tunnel, in the derivation of the formula used—factors whose effect could not have been foreseen. It was decided to use the values calculated from the globe-thermometer readings and the values given by these were as follows. At the lower air speed, the mean radiant temperature of the higher level of radiant heat was approximately 21°F above air temperature, and at the higher air speed the mean radiant temperature of the higher level of radiant heat was approximately 16°F above air temperature.

Physiological Effects

For sweat loss, final rectal temperature, final pulse rate and final skin temperature, the results at the lower and those at the higher air speed were treated as separate experiments.

Sweat loss. A summary of the analyses of variance is set out in Table 57. The mean values, each for two subjects, for the sixteen treatment combinations are set out in Table 58.

At the lower air speed an increase in the mean radiant temperature of 21°F produced an increase in the mean sweat loss of 4·9 g/kg at dry-bulb 90°F, but at 110°F it produced an increase of 10·1 g/kg. At the higher air speed an increase in the mean radiant temperature of 16°F produced approximately the same increase in the amount of sweat lost at 90°F (5·4 g/kg) as at 110°F (5·9 g/kg).

Table 59 sets out the same findings in a somewhat different fashion. This table shows that the average increase in the amount of sweat loss per degree Fahrenheit increase in mean radiant temperature ranged from 0·19 g/kg to 0·61 g/kg, depending upon the air temperature, humidity and air speed.

Final rectal temperature. At the lower air speed, none of the effects was significant and at the higher air speed only the direct effects of air temperature and radiant heat were significant. The mean values are set out in Table 60.

Final pulse rate. The effect of increasing the air temperature was significant at both the higher and the lower air speed, but the only other significant effect was the interaction of air temperature and radiant heat at the lower air speed. The mean values for the sixteen treatments are set out in Table 61.

Skin temperature. The mean value of the final skin temperature for each pair of subjects is set out in Table 62.

The direct effect of air temperature was, as might be expected, highly significant at both air speeds. At the lower air speed, both the R × H and the R × D × H interactions were significant. At the higher air speed, on the other hand, although the effect of radiant heat (R) was significant, none of the interactions involving R was significant. In no case did any effect involving R exceed the 5 per cent level of significance. There were no other significant effects.

Upper Tolerable Limits

In designing the experiment it was thought that the most difficult climate or climates used should approach, but not exceed, the upper tolerable environmental limits. While it was desired to gain all possible information on the probable effects of added radiant heat on the levels of air temperature, humidity and air speed which could be tolerated at the level of work used in the 'Queen Square Routine', it was considered necessary that all subjects should be able to complete the four-hour exposure, as previous experience had shown that in a factorial experiment of this nature the calculation of missing values was a most unsatisfactory procedure.

The line marked 'Probable limits for subject tolerance' shown in Fig. 14

cannot be considered as more than a well-informed guess based on the results of previous experiments, but Series V confirmed the belief that a dry-bulb temperature of 110°F and a wet-bulb temperature of 87·5°F at an air speed of 100 ft./min would probably represent an upper limit of tolerance at the level of added radiant heat used. Both subjects (7 and 8) at $D_2H_2A_1R_2$ almost failed to complete the task and may be classified as 'incipient collapses'.

Subject 7 while drinking water after the first work period complained of 'feeling sick' and stated that he had felt giddy while standing after step-climbing. He experienced no further trouble until he was standing for his standing-pulse-rate count after the third work period. It was then observed that he was cyanosed and that his pulse, which at first was 100 beats/min, suddenly accelerated and then became slow and weak and he was compelled to sit down. He complained again of feeling 'sick' and vomited 53 ml. of clear fluid. He recovered fairly rapidly but had to be assisted to the weighing machine.

During the third work period Subject 8 complained of abdominal pain but continued working. Whilst standing at the end of the work period, he suddenly became faint and was forced to sit down. He had to be assisted to the weighing machine. He apparently recovered during the following rest and completed the experiment without further incident, but it was obvious that he was distressed. A diagnosis of incipient collapse due to peripheral circulatory failure was made in both cases.

There are large personal differences in ability to withstand hot environments and the behaviour of these two subjects does not prove more than that the climate in question is close to the upper tolerable limit for some people. On the other hand, there is nothing to suggest that these two subjects were in any way abnormally sensitive to hot environments; they were both young, strong, physically fit and acclimatized to tropical conditions.

CONCLUSIONS

In many ways this series of experiments proved disappointing. The quantitative assessment of the effect of increasing the mean radiant temperature provided results that were in many ways equivocal, and there is little point in discussing them further at this stage as the subsequent series provided much more satisfactory material. On the other hand, the performance of this series of experiments provided necessary and valuable experience in operating the radiant-heat tunnel. Morever, the hitherto unsuspected importance of the need for further investigation into the methods of determining the level of mean radiant temperature was emphasized. The occurrence of two cases of incipient collapse at the highest level of stress investigated was also of value in that it provided further information on the upper tolerable levels of warmth for naturally acclimatized men. Disappointing and inconclusive though the results appeared to be, it was in fact fortunate that this shorter and more informal series of experiments was conducted before the major Series VI was embarked upon, and indeed their performance proved to be an economy of time and effort.

Series VI: Principal Physiological Investigation

The aims of Series VI have already been set out formally on p. 96. It followed closely on Series V and the choice of the levels of the various factors used in it was based on experience gained in that series of experiments.

METHODS

Experimental Design

The investigation was arranged in the form of a factorial experiment with five principal factors. These were air temperature (D), humidity (H), air speed (A), radiant heat (R) and clothing (N). Subjects (S) may be regarded as a sixth factor.

There were two levels of D, two levels of H, three levels of A, four levels of R and two levels of N, making in all 96 treatment combinations. Only one level of work rate was investigated, viz., alternate resting and step-climbing on a stool 12 in. high 12 times per min according to the usual 'Queen Square Routine' (p. 15).

The investigation was divided into two parts which were conducted separately. Part 1 was completed first and was followed almost immediately by Part 2. Part 1 consisted of all the treatment combinations involving D_1H_1 and D_2H_2, and Part 2 the remainder, i.e., all treatment combinations involving D_1H_2 and D_2H_1.

Eight subjects were used, four ($S_1 - S_4$) in Part 1 and four ($S_5 - S_8$) in Part 2. As the radiant-heat tunnel would accommodate only two subjects at a time two experimental sessions per day were held, one in the morning and one in the afternoon. In Part 1 subjects S_1 and S_2 performed all their experiments in the mornings and S_3 and S_4 performed theirs in the afternoons. Similarly, in Part 2 subjects S_5 and S_6 were treated in the mornings and S_7 and S_8 in the afternoons.

Clothing was interchanged between each member of a pair so that the subject who wore shorts during all the treatment combinations involving D_1 wore overalls at D_2, and similarly those subjects who wore shorts at D_2 wore overalls at D_1. This arrangement is illustrated in the following plan.

Air temp.	*Humidity*	*Air speed*	*Radiant heat*	*Subjects and clothing*			
				Morning		*Afternoon*	
Part 1							
D_1	H_1	A_1 to A_3	R_1 to R_4	S_1N_1	S_2N_2	S_3N_1	S_4N_2
D_2	H_2	A_1 to A_3	R_1 to R_4	S_1N_2	S_2N_1	S_3N_2	S_4N_1
Part 2							
D_1	H_2	A_1 to A_3	R_1 to R_4	S_5N_1	S_6N_2	S_7N_1	S_8N_2
D_2	H_1	A_1 to A_3	R_1 to R_4	S_5N_2	S_6N_1	S_7N_2	S_8N_1

Environmental Conditions and Clothing

The levels used for the various factors were based on the experience gained in Series V and were as follows:

D (air temperature)	D_1, 90 F; D_2, 110 F
H (humidity)	H_1, 16·5 mm Hg; H_2, 27·0 mm Hg
A (air speed)	A_1, 150 ft./min A_2, 200 ft./min A_3, 350 ft./min
R (radiant heat expressed as the amount by which the mean radiant temperature exceeded the air temperature)	R_1, 0 F (air temperature) R_2, 5·4 F R_3, 10·8 F R_4, 16·2 F
N (clothing)	N_1, shorts N_2, overalls over shorts

Allocation of Treatments

Subjects were allotted numbers 1 to 8 by lot. As it had been shown in trial runs that subjects underwent serious deterioration in their physical condition when submitted on two or more successive days to treatments involving the higher level of air temperature, the original intention of applying all the treatments in each part in an entirely random order (in which by chance several successive days might be allotted to treatments at the higher air temperature) could not be adhered to. The following procedure was therefore adopted. In each part all the treatments involving D_1 (D_1H_1 in the case of Part 1 and D_1H_2 in the case of Part 2) were randomized separately and a similar procedure was adopted for the treatments involving D_2 (D_2H_2 in the case of Part 1 and D_2H_1 in Part 2). Alternate days were then allotted to treatments involving D_1 and to treatments involving D_2. The first day was chosen by lot.

Experimental Procedure

The experimental procedure was that followed in Series V with the addition that the subjects were weighed and their heart rates, rectal temperatures and skin temperatures were measured at the mid-point of the long rest period intervening between the third and fourth work periods.

Fluid intake. As in Series V, the fluid intake during the experimental period was restricted to 1·5 l.; subjects were, however, given a further 500 ml. during the rest period of 20 min which preceded each experiment.

Acclimatization

Before the experiment proper, the subjects were acclimatized by a graduated exposure to hot conditions over a period of two weeks (12 working days). The first and the last day were used for uniformity trials and the experiment proper concluded with a third uniformity trial. (The results of the second and third uniformity trials indicated that there was no change in the degree of acclimatization during the experiment proper.)

Control of Mean Radiant Temperature

In the original design of the series it was intended that the four levels of radiant heat used should be such that the mean radiant temperature of the surroundings would be 0°F (walls at air temperature), 10°F, 20°F and 30°F respectively above air temperature. To achieve these results, calculations were made to determine what should be the average temperature of the panels in the radiant heat tunnel to produce, when due allowance had been made for the unheated ends, the mean radiant temperature desired. Before each experiment began, the walls of the tunnel were brought to the appropriate temperature and maintained there throughout the experiment by making hourly readings of the mean temperature of all the panels in the tunnel, together with spot checks on selected panels at shorter intervals, and by making adjustments where necessary.

It had been calculated that if the panel temperatures were maintained at 12·7°F, 25·3°F and 37·5°F above the temperature of the air, this would produce mean radiant temperatures that would be 10°F, 20°F and 30°F above the air temperature. Control of the mean panel temperatures was quite satisfactory and no difficulty was experienced, now that the modified switch-gear had been fitted, in maintaining the panels at these temperatures with less than 1°F variation.

At the conclusion of each experiment three globe thermometers were set up, at heights of 2 ft., 3 ft. 9 in. and 5 ft. 6 in. from the floor, in the position occupied by each subject. When these reached equilibrium, their temperatures, the temperature of the air passing over them, and the air speed over each were measured. Examination of the results of these measurements showed that, although the levels employed were consistent, they were not the intended values.

Calculation of the mean radiant temperature from the globe-thermometer readings according to the method of Bedford (1946) gave consistent values which exceeded the air temperatures by roughly half the amount expected. The mean radiant temperature at R_2 was 5·4°F, at R_3 10·8°F and at R_4 16·2°F above air temperature. This anomalous behaviour had already been noted in Series V, but as yet there was no unequivocal explanation. The work of Newling (1954), which was completed later, showed without doubt that the original calculations were in error and that the values obtained from the globe-thermometer readings were correct.

Little importance would have attached to these findings had they not meant that the range of radiant heat explored was only approximately half that originally intended. This provided one of the most important reasons for conducting a further series of experiments (Series VII) in which the range of the increment of radiant heat employed was considerably increased.

RESULTS

Sweat Loss per Kilogram of Body Weight

The analysis of variance of the results for sweat loss per kilogram of body weight is set out in full in Table 63. The relevant mean values are set out in Table 64.

In Table 63, no level of significance is attached to the values for D and H (air temperature and humidity) because the design of the experiment was such that a valid test of significance was not possible, but the size of the mean squares leaves no doubt that the effects were real and of very considerable magnitude, a conclusion confirmed by observation during the experiments. Table 64 shows that the average amount of sweat produced at the higher dry-bulb temperature (110°F) was 48·2 g/kg, more than twice that produced at the lower temperature (90°F)—23·2 g/kg. Similarly, the average amount of sweat produced by all the subjects in all the experiments at the higher humidity (27·0 mm Hg) was 38·5 g/kg and at the lower humidity (16·5 mm Hg), 32·9 g/kg.

Other effects, not involving the effect of radiant heat, may be dealt with briefly. On the whole, an increase in air speed produced a decrease in the amount of sweat (Table 64), but this effect cannot be considered apart from the effects of humidity and clothing. At the lower humidity (H_1), the effect of increasing the air speed was to produce a small but highly significant increase at the highest level (A_3). At the higher humidity (H_2), there was a reduction in the amount of sweat produced as the air speed was increased. The effect of increasing the air speed varied with the type of clothing worn. The average effect for men wearing shorts (N_1) was a slight fall when the air speed was increased from A_1 to A_2, followed by a rise when it was increased to A_3, but for men wearing overalls (N_2), increasing the air speed produced a consistent fall in the amount of sweat lost. These results are consistent with findings for previous experiments and need not be discussed further.

The effect of added radiant heat. The average effect of raising the mean radiant temperature was to increase the amount of sweat lost. A rise of 16·2°F in the mean radiant temperature produced, on the average, an increase of 5·2 g/kg of sweat—an increase of 0·32 g/kg for each degree rise in the mean radiant temperature (Table 64). Further, under all conditions investigated in the experiment, a rise in the mean radiant temperature (the other factors being held constant) resulted in an increase in the amount of sweat lost. The D × R interaction was significant; as Table 64 shows, an increase in mean radiant temperature had a greater effect at the higher air temperature than at the lower.

No other first or higher order interactions involving radiant heat were significant. This is to say that, within the range of conditions investigated, altering the level of air speed, humidity or clothing had no effect on the increase in the amount of sweat produced by increasing the level of mean radiant temperature. In particular, it should be noted that the amount of clothing worn (shorts or overalls) did not alter the effect of increasing the mean radiant temperature.

Examination of the mean values for air temperature and radiant heat in Table 64 suggested that the response to equal increments of mean radiant temperature might be curvilinear. The sum of squares for R in the original analysis of variance was therefore split into its linear, quadratic and cubic components with the results set out in Table 65. When these results were plotted, the curvilinearity was apparent and suggested that as the amount of radiant heat was increased its effect would be less.

There is another explanation more likely on physiological grounds. There is a limit to the amount of sweat which any subject can produce under given conditions of salt and water intake, and as this is approached the response as measured in terms of sweat production will decrease, although the actual physiological strain may be greatly increased; in other words, the response curve tends to flatten out as the upper limit of tolerance is approached. The falling off in sweat production at the uppermost level of radiant heat was chiefly apparent at the higher air temperature and, as it was obvious to the observers during the course of the experiment that the subjects working in overalls at the higher levels of air temperature and humidity were inneed approaching their upper tolerable limits, this simple physiological explanation appeared to be adequate.

There remained, however, some doubt which could only be resolved by exposing the subjects to the highest levels of radiant heat that could be produced within the tunnel at an air temperature such that the conditions were still well below the upper tolerable limits of environmental stress. The necessity for this was met in the design of Series VII.

Final Rectal Temperature

The relevant mean values are set out in Table 66. There is general agreement between these results and those for sweat loss. There are some differences, however, which may be indicated briefly. The main effect of clothing was significant; men wearing overalls generally had higher body temperatures than men wearing shorts. It is interesting to note the importance of the effect of the level of humidity. At the lower level of humidity there was, on the average, no difference between the body temperatures of men wearing shorts and men wearing overalls, but at the higher humidity the wearing of overalls produced a significant rise in body temperature. This may equally well be expressed by saying that for men in shorts variation in the humidity was without effect, but when overalls were worn an increase in humidity produced a significant rise in body temperature. On the whole, increasing the air speed had little effect at the lower level of humidity, but at the higher level of humidity increasing the air speed produced a substantial fall in the final rectal temperature, indicating the importance of adequate air movement at the higher levels of humidity.

The effect of added radiant heat. The main effect of added radiant heat was highly significant. On the average, increasing the mean radiant temperature by 16·2°F increased the final rectal temperature by 0·31°F. Only one interaction involving R was significant (the second order interaction D × A × R) and that only at the 5 per cent level. In the appropriate part of Table 66 it can be seen that the changes in rectal temperature with changes in air speed were capricious; it is difficult to give a satisfying physiological explanation. It is no doubt due to this variability that, although the effect of increasing the level of radiant heat from R_1 to R_4 at dry-bulb 110°F produced an average increase in the final rectal temperature of 0·42°F compared with only 0·21 at dry-bulb 90°F, it was not possible to show that this represented a real difference. The most that can be said is that it would appear that increasing the level of air temperature showed some tendency to increase the effect of added radiant heat as measured by the changes in rectal temperature.

Final Pulse Rate

The appropriate mean values are given in Table 67. As in the other variates previously examined, the effects of air temperature and humidity were large and it may be assumed that they were real. The effect of air speed varied with the level of air temperature and humidity but, except at the higher level of humidity, changes in air speed did not produce marked changes in the pulse rate. At the upper level of humidity, increasing the air speed from 150 to 350 ft./min resulted in a fall in the pulse rate of 12 beats per min. The effect of clothing was also interesting. At the lower level of humidity clothing had no effect on the pulse rate, but at the higher level the wearing of overalls produced a marked increase in the pulse rate.

The effect of added radiant heat. With an increase in added radiant heat there was an increase in pulse rate. On the whole, this increase was not large (see Table 67) and the effect depended upon the level of air temperature and humidity. At the lower level of air temperature (90°F) the effect was small and inconstant. At the higher air temperature (110°F) the effect, although still somewhat irregular, was much larger. At the lower level of humidity the effect, although regular, was less than half of that at the higher level of humidity.

Final Skin Temperature

The appropriate mean values are set out in Table 68. The main effects of air temperature and humidity were probably real. The average result of increasing the air speed was to reduce the skin temperature, but the effect was much larger at the higher level of humidity. The level of clothing worn was without effect. Neither the main effect nor any of the interactions involving clothing was significant.

The effect of added radiant heat. The effect of raising the mean radiant temperature was to increase the mean skin temperature, and this effect was independent of the level of the remaining factors. It is noteworthy that the wearing of overalls had no effect on the change in skin temperature with increasing radiant heat.

Comparison of the Physiological Effects of Added Radiant Heat

It is convenient at this stage to summarize the conclusions to be drawn concerning the effect of increasing the mean radiant temperature on the stress imposed by the environment, as measured by the physiological response of the subject. This can conveniently be done by considering a comparative table of the results of the several analyses of variance.

In Table 69 is set out a short summary of the analyses of variance already discussed. There is also included a summary of the analyses of variance for skin temperature after the third work period and at the mid-point of the long rest period between the third and fourth work periods. The reason for this inclusion is that whereas the results for sweat loss, pulse rate and rectal temperature are reasonably consistent among themselves, the results for final skin temperature differ from them in certain respects. It seemed possible that this was perhaps true only for the final skin temperature but it would appear that this was not so, as the results for skin temperature are in reasonable agreement between themselves.

The most striking fact that emerges is that the direct effect of added radiant heat (R) is uniformly significant throughout. Another important finding is that for skin temperature, whenever it was measured, the result of increasing the mean radiant temperature was not affected by the level of the remaining factors.

On the other hand, there is agreement between the results for sweat loss, rectal temperature and pulse rate that the effect of increasing the mean radiant temperature depends upon the level of the air temperature (in the case of rectal temperature the D × A × R interaction is significant). The results for final pulse rate alone suggest that the effect of added radiant heat is dependent upon the level of humidity—at the upper level of humidity a given increase in the mean radiant temperature produces a greater effect than at the lower level of humidity.

It is to be particularly noted that the effect of radiant heat was not altered by the clothing worn. No interaction involving clothing and radiant heat reached the 5 per cent level of significance. It has always been thought that clothing protects the wearer from the effects of high mean radiant temperature, and indeed common experience from the time of Blagden (1775) onwards has supported this. It must be emphasised, therefore, that these results apply only to the conditions of these experiments, more particularly the level of mean radiant temperature employed, the type of clothing and the duration of the experiment. At very much higher levels of radiant heat, with other types of clothing and with shorter exposures, the results might well be otherwise. In short exposures to fierce radiation, the insulation afforded by the clothing delays the attainment of equilibrium. Under the conditions studied, what has been gained by protection from radiant heat has been lost by interference with evaporative cooling.

Series VII: Supplementary Physiological Investigation

After the conclusion of Series VI it was evident that further information was necessary on a number of points. The most important of these was the question of whether the conclusions arrived at, in particular those relating to the effect of the amount of clothing worn, were valid at higher levels of added radiant heat. Another was that of the relation between the stress produced by increasing the air temperature and that produced by increasing the mean radiant temperature. With respect to this last point, it was thought that the gap between the two levels of air temperature used in the preceding experiments had been unduly large.

METHODS

The design of this series of experiments was dictated by the environmental conditions used, and the choice of the latter was severely limited by the conditions which the tunnel could produce. It was decided to use an air temperature of 100°F, as this lay midway between the values of 90°F and 110°F used in the previous series, and it was found by experiment that the highest mean radiant temperature that could be achieved in the tunnel with control of this air temperature still maintained was, as calculated from the panel temperatures, 160°F. This suggested that four levels of radiation could be employed: mean radiant temperatures of 100°F, 120°F, 140°F and 160°F. The first two of these conditions, it was thought, would then correspond with the two levels of radiation chosen for Series VI in which the mean radiant temperatures were 0°F and 20°F in excess of the air temperature. As in the case of Series VI, these calculations were shown later to be in error; the actual increments were found to be 10·8°F, 21·6°F and 32·4°F, but the relationship with Series VI, of course, still held good. At these levels of radiant heat it was impossible to maintain the lower level of humidity (16·5 mm Hg) employed in Series VI, so that it was necessary to use only one level of humidity, 27·0 mm Hg, corresponding to the upper level (H_2) used in Series VI. This partial pressure of water vapour corresponds to a wet-bulb temperature 85·3°F at an air temperature of 100°F.

Preliminary operation of the tunnel under these conditions showed that maintenance of the chosen air temperature at the highest levels of radiant heat which were to be used was impossible at the lowest level of air speed employed in Series VI, so it was decided to use only two air speeds, 200 ft./min and 350 ft./min, which corresponded to A_2 and A_3 used in Series VI.

The ability of the subjects to withstand high levels of stress presented no special difficulty in planning the series as it was considered, on the basis of experience in Series VI, that the highest levels that had been chosen for use would be less than those experienced at the higher air temperature in Series VI, and so within the capacity of the subjects. This belief proved to be correct.

The usual two levels of clothing—shorts and overalls worn over shorts—were adopted, but it was arranged that all subjects should wear both shorts and overalls in each environment in order to prevent any ambiguity arising from subject-clothing interaction.

The levels used for the various factors can be summarized as follows.

A (air speed)	A_2, 200 ft. min A_3, 350 ft. min
R (mean radiant temperature)	R_1, 100 F (increment 0 F) R_3, 110·8 F (increment 10·8 F) R_5, 121·6 F (increment 21·6 F) R_7, 132·4 F (increment 32·4 F)
N (clothing)	N_1, shorts N_2, overalls

It will be seen that this is a simple factorial experiment involving three factors: air speed, added radiant heat and clothing. The two levels of air speed, 200 ft./min and 350 ft./min, are referred to as A_2 and A_3 to emphasise their identity with the levels so designated in Series VI. The four levels of radiant heat are referred to as R_1, R_3, R_5 and R_7 to indicate the identity of R_1 and R_3 with the levels so designated in Series VI, and to emphasise that the increment of 10·8°F between succeeding levels is twice that employed in Series VI. R_1, therefore, indicates a mean radiant temperature of 100°F, R_3 a mean radiant temperature of 110·8°F, R_5 a mean radiant temperature of 121·6°F, and R_7 a mean radiant temperature of 132·4°F. Three subjects ($S_1 - S_3$) were used, as it had been demonstrated that it was possible to arrange three subjects in the tunnel at the corners of an equilateral triangle without introducing a measurable error into the level of radiant heat to which they were exposed. This simple experimental plan was chosen largely because of the simplicity of the subsequent analysis of variance.

All the subjects were exposed to all combinations of all the factors and the treatments were applied in a random order.

The three subjects, and one reserve, were again volunteers from the Army. So that their results would be strictly comparable with those of the subjects of Series VI, they were acclimatized by a similar routine to that employed previously (p. 107). (The results of uniformity trials revealed that the process of acclimatization was apparently complete by the twelfth day and did not alter during the course of the experiment.)

The experimental routine adopted was precisely that used for Series VI, the 'Queen Square Routine', and the measurements (weight loss, rectal temperature, pulse rate and skin temperature) were made in exactly the same way. Fluid intake was again restricted to 500 ml. of water before entering the chamber and 1·5 l. during the course of the experiment.

Dry- and wet-bulb temperatures were recorded at the front and rear of the tunnel at five-minute intervals as in the two previous series but a refinement was added by the introduction of a system of continuous aspiration of the Assmann psychrometers, by means of an electrically driven fan situated outside the chamber. The air speed was adjusted by controlling the fan speed, an innovation introduced in Series VI. The mean radiant temperature was checked by continuous readings of panel temperatures and, at the end of each experiment, by the use of nine globe thermometers, three, arranged as in Series VI (p. 107), occupying the position of each subject.

RESULTS

Sweat Loss

The formal analysis of variance for the sweat loss per kilogram of body weight is set out in full in Table 70. The appropriate mean values for significant effects are set out in Table 71. The striking feature of the analysis of variance was its decisiveness. Effects which were significant were overwhelmingly so and the non-significant effects in no case approached the level of significance.

The effect of added radiant heat. In the analysis, the variance due to the effect of added radiant heat was split into its linear, quadratic and cubic components. The linear component was overwhelmingly significant and the remaining two were not significant, which would suggest that the effect of added radiant heat was constant over the range investigated.

None of the interactions involving radiant heat was significant; this indicates that the effects were unaltered by the amount of clothing worn or by the variations in the air speed, and that the response did not vary from subject to subject.

Reference to Table 71 will show that increasing the mean radiant temperature from R_1 to R_7, an increment of 32·4°F, resulted in an increase in the amount of sweat produced of 10·2 g per kilogram of body weight or 0·31 g per 1°F increase in the mean radiant temperature.

The effects of clothing and air speed. Under all conditions, wearing overalls imposed a greater stress than wearing shorts. The average effect was to increase the amount of sweat produced by 6·1 g per kg body weight above that produced when only shorts were worn (Table 71). The effect of changes in air speed depended on the amount of clothing worn. Increasing the air speed from 200 to 350 ft./min increased the sweat loss for men wearing shorts but decreased the amount lost for men wearing overalls. This illustrated very nicely the interplay of the two factors of increased convective gain and increased evaporative loss of heat at air temperatures above skin temperature. Overalls protected from the one but hindered the other.

Final Rectal Temperature

A summary of the appropriate mean values is set out in Table 72.

The effect of added radiant heat. The average effect of an increase in the mean radiant temperature on the final rectal temperature was highly significant, but, in contrast with the findings for sweat loss, the effect varied significantly with other factors. The interactions with subjects, air speed and clothing were all significant.

For all subjects, the difference between the rectal temperature at R_7 and that at R_1 amounted to an increase of 0·63°F and the individual increases for all three subjects were very close to this. However, the increase in rectal temperature with each succeeding increase in the level of radiant heat was by no means regular and differed from subject to subject. This will be discussed in greater detail later.

The effect of increasing the mean radiant temperature was, on the whole, greater at the lower air speed than at the higher and, whereas at the lower air speed the effect of increasing the level of radiant heat tended to increase with successive increments, at the higher air speed the effect of added radiant heat tended to diminish with successive increments. Clothing, also, altered the response to added radiant heat. The effect of increasing the mean radiant temperature over the range 0°F to 32·4°F was greater for men wearing overalls than for men wearing shorts and the pattern of the response differed. For men wearing shorts there was a fall followed by a rise, but with overalls the rise was continuous although the amount of increase diminished at the higher levels.

The effects of other factors. The main effects of both clothing and air speed were highly significant, which in this case meant that, on the whole, men wearing overalls had a higher rectal temperature than men wearing shorts, and that a higher rectal temperature occurred at the lower air speed than at the higher. These were, of course, merely average effects and must be interpreted only in conjunction with possible modifying factors. The interaction of radiant heat with clothing and air speed has just been discussed. There remains the interaction between these two factors themselves. It is particularly interesting that for men wearing shorts the change in air speed was without effect on the rectal temperature, but for men wearing overalls an increase in the air speed produced a decrease in the rectal temperature.

Final Pulse Rate

The appropriate significant mean values are to be found in Table 73. The findings are very similar to those for sweat loss.

The average pulse rate for men wearing overalls was higher than that for men wearing shorts, but the difference was reduced at the higher air speeds because increasing the air speed was without effect on the pulse rate of men wearing shorts, but produced a very substantial fall in the case of men wearing overalls.

The effect of added radiant heat. Increasing the mean radiant temperature resulted in an increase in the final pulse rate and this increase was much greater in men wearing overalls than in men wearing shorts. It is worth noting that there was no change in the pulse rate between R_3 and R_5 when either shorts or overalls were worn, but this may of course have been merely a chance effect. Alterations in air speed did not effect the increase in pulse rate that accompanied the increase in mean radiant temperature.

Final Skin Temperature

The significant mean values are set out in Table 74.

Increasing the mean radiant temperature caused an increase in the mean skin temperature, and this result was not affected by alteration in the levels of the remaining factors. The effects of alterations in the level of both air speed and clothing were significant. Increasing the air speed produced a fall in the skin temperature, and the mean skin temperature was approximately 0·8°F lower at the higher air speed (Table 74). Wearing overalls increased the skin temperature 1·4°F. It is of some importance that the interaction between radiant heat and clothing was not significant. It might have been expected that, at the upper level of radiant heat, the protection offered by wearing overalls would have become important. It is also worth noting, in passing, that an increase in the amount of clothing worn produced a much greater rise in the skin temperature of subject No. 1 than in that of the remaining two subjects.

Comparison of the Physiological Effects of Added Radiant Heat

Table 75 sets out a brief summary of the results of the analyses of variance that have been discussed. For the sake of ease of comparison with the similar summary in the account of Series VI (Table 69), the results for the skin temperature at the end of the third work period and at the mid-point of the long rest period between the third and fourth work periods have been included.

Examination of the summary emphasizes the consistency of the effects of increasing the mean radiant temperature. There were increases in sweat loss, rectal temperature, skin temperature and pulse rate and, despite the differences that existed between subjects, there was little to suggest that the effects differed from subject to subject. Only in the case of rectal temperature was the reaction S × R significant and then only at the 5 per cent level. It is equally clear that the wearing of heavier clothing increased the strain produced by a given climatic stress, but that the degree varied with the level of air speed.

There remains the vexed question of the interaction between the effect of increasing the mean radiant temperature and the amount of clothing worn. If we base our conclusions solely on the amount of sweat lost the answer is that the level of clothing is without effect. On the other hand, the findings with respect to pulse rate suggest that the wearing of overalls was deleterious. Increasing the mean radiant temperature by 32·4°F produced in the case of men wearing shorts an increase in the pulse rate of 14 beats per min, but for men wearing overalls the increase was 38 beats per min.

The evidence provided by the skin temperature at the middle of the long rest period likewise suggests that the wearing of overalls was deleterious. Over the range of mean radiant temperature investigated, for men wearing shorts there was an increase in the mean skin temperature of 0·77°F, but for men wearing overalls there was an increase of 1·62°F. The evidence provided by the rectal temperature was equivocal. Although the increase over the whole range for men wearing overalls (0·72°F) was greater than that for men wearing shorts (0·54°F), the rise with each succeeding increment of mean radiant temperature tended to decrease for men wearing overalls but to increase for men wearing shorts.

The conclusion appears to be that, over the range of mean radiant temperature investigated, there was no convincing evidence that the wearing of overalls conferred an advantage over the wearing of shorts; indeed, the weight of evidence would seem to support the contrary view.

Discussion

The Physiological Effects of Radiant Heat

The first aim of these three series of experiments (Series V, VI and VII) was 'To assess, in terms of rate of sweat loss, elevation of body temperature, increase in pulse rate and changes in skin temperature, the effect of increasing the mean radiant temperature of the surroundings at different levels of air temperature, humidity, air speed and clothing . . .' (p. 96). The relevant results, reported in earlier parts of this chapter, provided information of considerable value. In retrospect, however, it was clear that the value of Series V, VI and VII would have been greatly enhanced if they had been designed to permit partitional calorimetry (Winslow, Herrington & Gagge, 1936*a*), as a direct comparison could then have been made of the amounts of heat gained by convection and radiation.

Unfortunately, partitional calorimetry was not practicable. Ideally, this requires a lengthy period in which the subject is in equilibrium with his environment. During this period the metabolic rate can be measured, skin temperatures determined with accuracy and, since the body is in equilibrium with the environment, heat storage, which is notoriously difficult to measure, can be neglected. In the experiments as performed, with their alternating periods of rest and work, there was no period in which equilibrium was maintained. Metabolic rates were not measured. Skin temperatures were recorded only at the beginning and end of each work period. The final body temperatures were always higher than the initial body temperatures so that some degree of heat storage occurred. Moreover, it was not possible to say that the weight loss recorded represented accurately the amount of water evaporated from the skin and lungs.

Nevertheless, it seemed important that an attempt should be made to obtain some estimate of the relative magnitude of the heat loads due to radiation and convection, and it was decided to attempt an analysis of the heat gain by the method of Haines and Hatch (1952) and to compare the calculated amount of sweat required to maintain equilibrium with the actual loss of weight observed. In order to avoid the complicating effects of clothing, only the values for men wearing shorts were examined.

The results obtained can be regarded only as estimates, because in order to use the experimental values certain assumptions were made. The evaporative water loss per hour was taken to be one-fourth of the total weight lost in 4 hr; the average skin temperature was assumed to be the mean of all measurements made in the four-hour period; the metabolic rate was taken to be the average value determined for the 'Queen Square Routine', viz., 106 kcal.m^{-2}.hr^{-1}, (748 B.Th.U.hr^{-1}); and it was assumed that storage could be neglected.

Heat exchange by radiation was calculated from the formula

$$R = eKA_r(T_w^4 - T_s^4)$$

where R is the heat transfer by radiation (B.Th.U.hr^{-1}), K the universal radiation constant ($1{\cdot}73 \times 10^{-9}$ B.Th.U.hr^{-1}.ft^{-2}.°F^{-1}), A_r the effective radiation area of a man (taken to be 15·5 sq. ft.), T_w the mean radiant temperature (°F Abs.), T_s the average skin temperature (°F Abs.) and e the emissivity of the skin (taken to be unity).

The rate of heat transfer by convection was calculated from the formula

$$C = K_c.A_c(t_s - t_a)$$

where C is the rate of heat exchange by convection (B.Th.U.hr^{-1}), K_c the coefficient of heat exchange by convection (B.Th.U.ft^{-2}.hr^{-1}.°F^{-1}), A_c the effective convection area (19·5 sq. ft.), and t_s and t_a the skin and air temperatures respectively (°F). Using the coefficient of convection obtained by Nelson, Eichna, Horvath, Shelley & Hatch (1947) ($K_c = 0{\cdot}11\sqrt{V}$ where V is the air speed in ft.min^{-1}) the equation simplifies to

$$C = 2{\cdot}1\sqrt{V}(t_s - t_a).$$

Table 76 sets out the respective contributions to the total heat load of metabolism, radiation and convection calculated in this fashion for subjects wearing shorts at an air speed of 200 ft./min, at both levels of humidity, at air temperatures of 90°F and 110°F, and at R_1 (no added radiant heat) and R_4 (a radiant heat increment of 16·2°F). This table demonstrates the reason for the D × R interaction (the effect of added radiant heat is increased by an increase in air temperature). Increasing the mean radiant temperature from R_1 to R_4 at dry-bulb temperature 90°F increases the radiation component by 283 B.Th.U., whilst increasing the mean radiant temperature from R_1 to R_4 at dry-bulb 110°F increases the radiation component by 354 B.Th.U. The explanation depends essentially on the fact that when the air temperature is increased from 90°F to 110°F in these experiments, because the walls are maintained at air temperature the mean radiant temperature also increases from 90°F to 110°F. An increment in mean radiant temperature of 16·2°F at the lower air temperature increases the mean radiant temperature from 90°F to 106·2°F. At the higher air temperature it increases the mean radiant temperature from 110°F to 126·2°F. However, as the heat exchange by radiation between the body and the environment is proportional to the difference between the fourth power of the absolute temperature of the skin and the fourth power of the absolute mean radiant temperature, the result is necessarily that the same increment of mean radiant temperature results in a greater increase in the radiation component of the heat gain at an air temperature of 110°F than at 90°F.

The increase in mean radiant temperature which accompanies an increase in air temperature in these experiments has a further important result. At R_1 (no added radiant heat) the exchange by radiation at 90°F is a loss of 47 B.Th.U.; at an air temperature of 110°F there is a substantial gain (275 B.Th.U.) by radiation, so that of the total difference in the heat load at 90°F and 110°F (827 B.Th.U.) no less than 322 B.Th.U. are due to the increased mean radiant temperature.

The relative magnitude of the contributions made by radiation and convection to the total heat load with variations in the mean radiant temperature is best appreciated from the results given for Series VII in Table 77. At the first level, R_1, where there is no added radiant heat, the radiation component is nevertheless of the order of half the convective heat load, though both are small compared with the metabolic heat production. At the second level, R_3, the radiation component is approaching twice the value of the convection component, and at the highest level, R_7, the radiation component exceeds the heat of metabolism.

On account of the assumptions made in the calculations, the values set out in Tables 76 and 77 are of necessity inexact, but it will be noted that there is good agreement between the calculated values for $M + R + C$ (metabolism plus radiation plus convection) and the heat equivalents of the sweat loss. This agreement between the observed and calculated evaporative losses would seem to indicate that the results are more reliable than might be expected from the approximations used in deriving them.

Other Investigations of the Effects of Radiant Heat

There have been few other systematic investigations of the effects of added radiant heat with which the present studies might be compared. Of these the most important is that conducted by Humphreys, Imalis & Gutberlet (1946). They conclude that 'The effect of radiant heat on physiological reactions is much less than had been anticipated; this is particularly true at the higher effective temperatures.' In their summary they further state 'The effect of radiant heat on physiological reactions decreases as the effective temperature increases and becomes surprisingly small as the upper limits of endurability are reached.' Considerable importance has been attached to this latter statement by other workers, and it has been extensively quoted. For example, Missenard (1948) requotes it as follows—'*Il apparait qu'au fur et à mesure que la température effective s'élève* (*il s'agit evidement ici de la température effective calculée d'après les équivalences de passage*)*, l'importance d'une variation de la température radiante moyenne diminue*' (italics his).

This conclusion by Humphreys *et al.* (1946) is in part based on Fig. 15(a) (reproduced from their paper) in which lines of equal rectal temperature are plotted, using effective temperature and elevation of mean radiant temperature above air temperature as co-ordinates. From this figure it can be seen that at an effective temperature of 80°F an increase of 40°F in the mean radiant temperature is equivalent to an increase of 10°F in the effective temperature; at an effective temperature of 84°F, the same increase in the mean radiant temperature is equivalent to an increase of 7°F in the effective temperature;

at 88°F it is equivalent to 4°F; at 93°F it is equivalent to only 2°F, and so on. This would appear to support the conclusions quoted.

If, however, the value of the rectal temperature is plotted against the corresponding value for the effective temperature of those environments without added radiant heat, the result illustrated in Fig. 15(b) is obtained. It will be seen

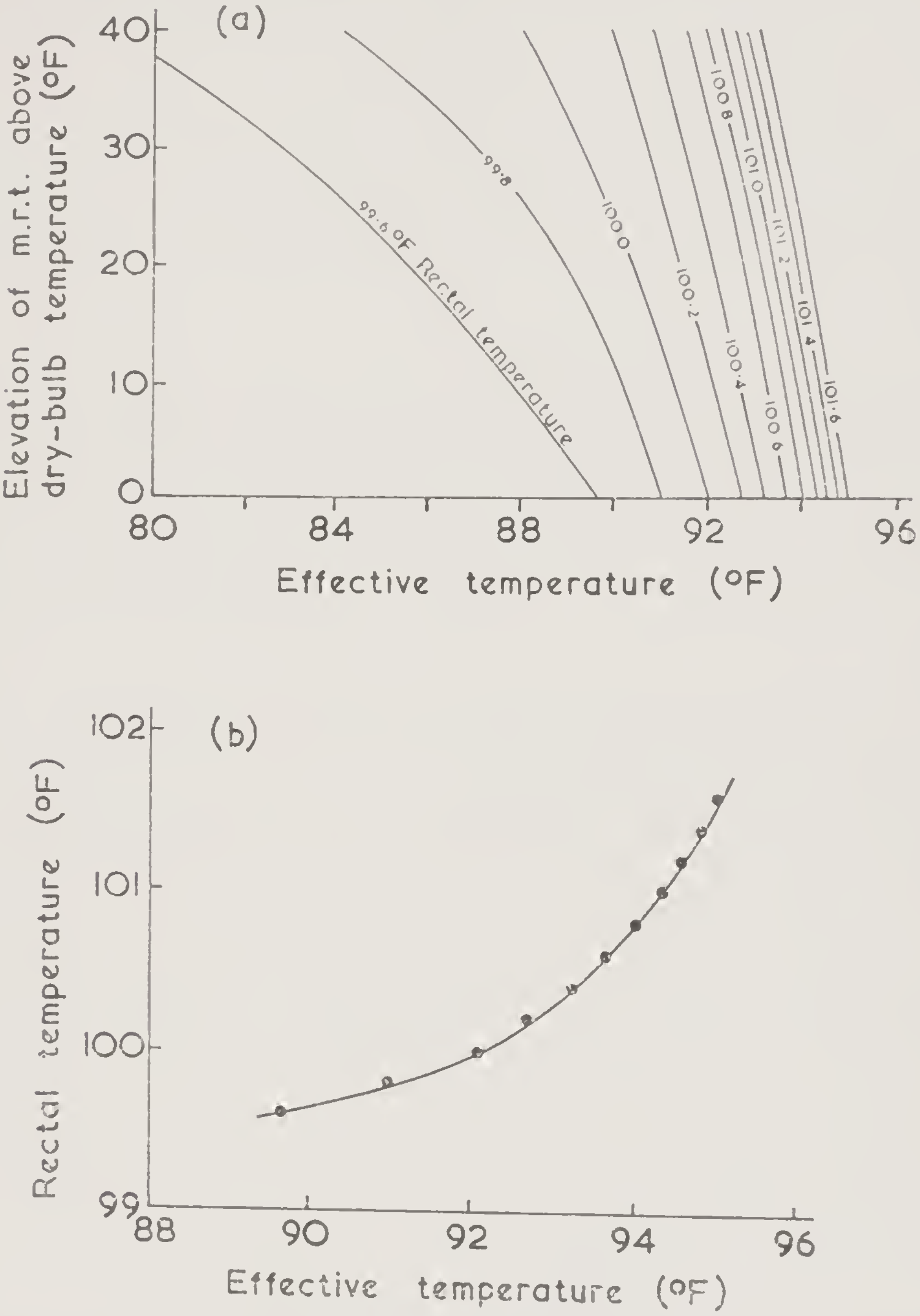

FIG. 15. (a) The relation between rectal temperature and elevation of mean radiant temperature above dry-bulb temperature at various levels of effective temperature as presented in their paper by Humphreys *et al.* (1946).

(b) A re-plotting of the values of the rectal temperature in (a) for environments with no added radiant heat.

that the relation is not linear but that each successive increment on the Effective Temperature Scale produces a greater effect on the physiological response than the preceding increment.

Assessing the effect of increasing the mean radiant temperature in terms of the effect of increasing the effective temperature can be very misleading unless this is borne in mind. This point is further illustrated by Table 78 which presents the findings of Humphreys *et al.* (1946) in a somewhat different way. In environments without added radiant heat an increase of 1°F in the effective temperature from 90°F to 91°F raises the rectal temperature 0·15°F, but the same increase in the effective temperature from 92°F to 93°F raises the rectal temperature 0·32°F—twice as much. Furthermore, increasing the mean radiant temperature by 40°F at an effective temperature of 90°F raises the rectal temperature 0·59°F, but the same increase in the mean radiant temperature at 93°F produces an increment of 1·30°F in the rectal temperature.

The conclusion is that, contrary to the expressed views of Humphreys *et al.* (1946), a given increment in the mean radiant temperature produces an increasingly greater physiological effect as the effective temperature is increased, which is in general agreement with the findings in Series V, VI and VII.

The P4SR and Mean Radiant Temperature

The results of Series V, VI and VII make it possible to examine the accuracy with which the P4SR nomogram predicts the amount of sweat lost in environments in which the mean radiant temperature exceeds the air temperature. This is of some importance for, whereas the P4SR nomogram in general was based on the results of over 1,000 individual four-hour experiments, the correction applied in the nomogram for the effects of added radiant heat is dependent upon the results of a very much smaller number (8 pairs) of experiments (see Appendix).

The P4SR was calculated for all the environments used in Series V, VI and VII at the appropriate metabolic rates and levels of clothing. Against these values were plotted the mean values for the total sweat lost by the two subjects exposed to each set of conditions in the experiments, and the appropriate regression line was calculated. In all cases the relation between the observed and predicted value was found to be linear.

As 'naturally acclimatized' men were used in Series V and artificially acclimatized men in Series VI and Series VII, it was considered advisable to treat the results of Series V separately from those of Series VI and VII, which were combined. The results for Series V may be expressed as follows:

For all values: $Y = 2{\cdot}145 + 0{\cdot}7832(x - 2{\cdot}1875)$

Experiments without added radiant heat: $Y = 1{\cdot}931 + 0{\cdot}7986(x - 1{\cdot}8625)$

Experiments with added radiant heat: $Y = 2{\cdot}359 + 0{\cdot}7963(x - 2{\cdot}5125)$

where x is the P4SR value and y is the observed sweat loss.

These results are illustrated in Fig. 16 which shows also the 95 per cent confidence limits for the first equation. Statistical examination of these regression equations shows that the three lines do not differ significantly either in slope or position. It may, therefore, be concluded that in this series of experiments the P4SR nomogram predicts the sweat loss for environments in which the mean radiant temperature is above the air temperature as well as it does for environments in which the mean radiant temperature is equal to the air temperature.

When the observed values for sweat loss were plotted against the predicted (P4SR) values for Series VI and Series VII, the results shown in Fig. 17 were obtained.

The appropriate regression lines are

For all values: $Y = 2{\cdot}328 + 0{\cdot}7711(x - 2{\cdot}620)$

Experiments without added radiant heat: $Y = 2{\cdot}129 + 0{\cdot}8084(x - 2{\cdot}275)$

Experiments with added radiant heat: $Y = 2{\cdot}394 + 0{\cdot}7533(x - 2{\cdot}724)$

where, as before, x is the P4SR value and y is the sweat loss.

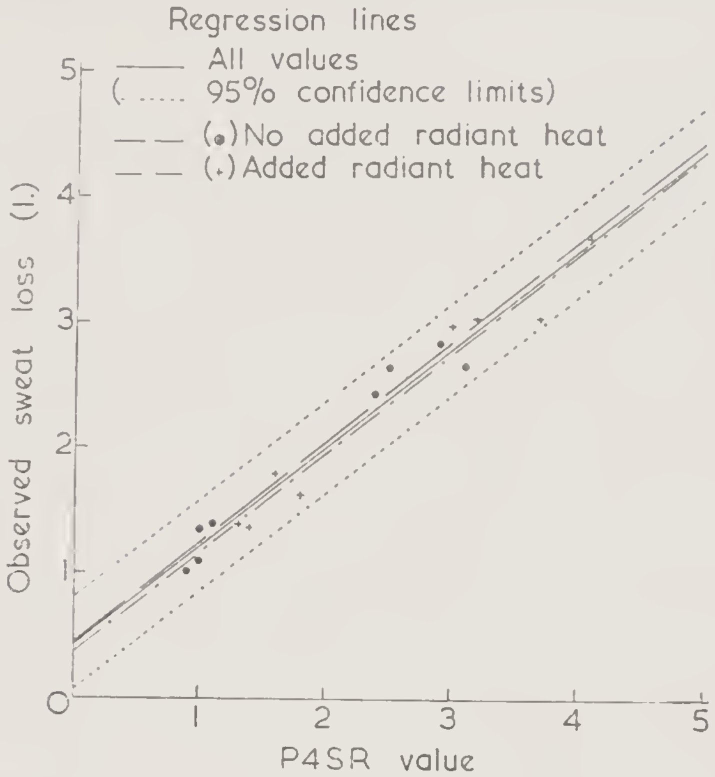

FIG. 16. Series V. The relation between observed sweat loss and the calculated P4SR Index.

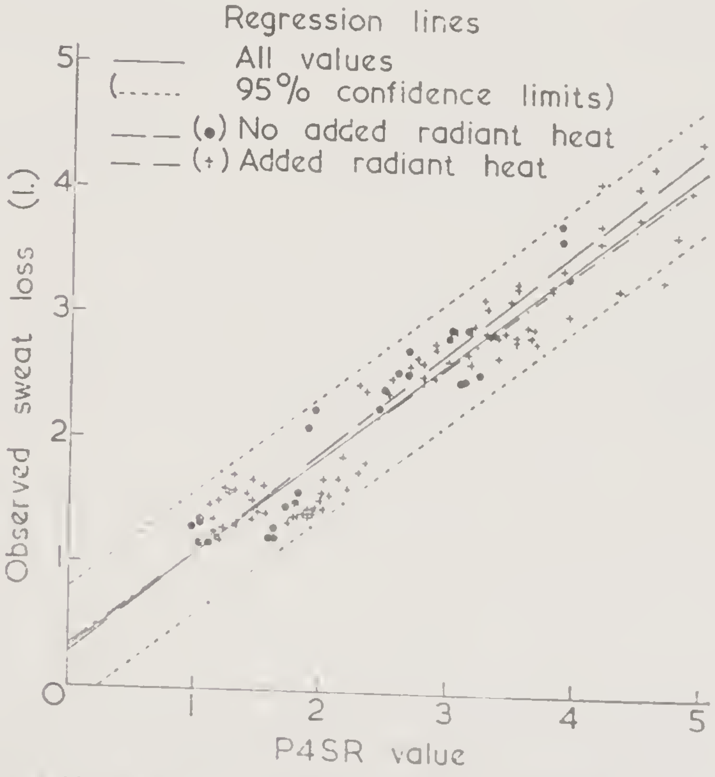

FIG. 17. Series VI & VII. The relation between observed sweat loss and the calculated P4SR Index.

There is no significant difference between the regression coefficients (*b*) for all three lines, i.e., they all have the same slope. Nor do they differ significantly in position. It may be concluded, therefore, that, in the terms of the definition, for fit acclimatized young men the value for the P4SR predicts the sweat loss equally accurately for environments in which the surroundings are above air temperature and those in which the surroundings are at the temperature of the air.

Corrected Effective Temperature

In their original form the Effective Temperature Scales made no allowance for exchange of heat by radiation between the subject and his environment. Bedford (1946) suggested that a satisfactory adjustment for the effects of radiation could be made in the Effective Temperature Scale by substituting for the dry-bulb temperature of the environment the reading of the globe thermometer in that environment—a suggestion that arose directly from the work of Vernon (1930, 1932). The new scales of effective temperature thus devised were called the 'Corrected Effective Temperature Scale (Normal)' and the 'Corrected Effective Temperature Scale (Basic)', which corresponded to the 'normal' and 'basic' scales of the original authors.

The workers at the National Hospital conducted a short series of experiments to test the adequacy of the correction proposed by Bedford and concluded (McArdle *et al.*, 1947) that 'these experiments therefore do not fully support Bedford's hypothesis'. It became a matter of considerable importance, therefore, in view of the widespread acceptance of the Corrected Effective Temperature Scale, to examine the validity of this conclusion.

Corrected effective temperature and sweat loss. In Figs. 18 and 19 the mean sweat loss (expressed as grams per kilogram of body weight) of the subjects of Series VI and Series VII for each combination of environmental conditions has been plotted against the appropriate value on the Corrected Effective Temperature Scale. Fig. 18 represents the sweat losses of men wearing overalls, plotted against 'normal' effective temperature values, and Fig. 19 represents the sweat losses of men wearing shorts, plotted against 'basic' effective temperature values. Identical scales are used in both figures. The four digits which appear against each point identify the levels of the environmental factors in the climate represented by the point.

The first digit refers to the air temperature:
1, 90°F; 2, 100°F; and 3, 110°F.

The second digit refers to the water-vapour pressure:
1, 16·5 mm Hg; and 2, 27·0 mm Hg.

The third digit refers to the air speed:
1, 150 ft./min; 2, 200 ft./min; and 3, 350 ft./min.

The fourth digit refers to the level of the mean radiant temperature above air temperature:
1, 0°F; 2, 5·4°F; 3, 10·8°F; 4, 16·2°F; 5, 21·6°F; and 7, 32·4°F.

On examination of these points it was clear that the relation between sweat loss and effective temperature was not linear, but could be represented by a quadratic equation of the form

$$Y = ax^2 + bx + c.$$

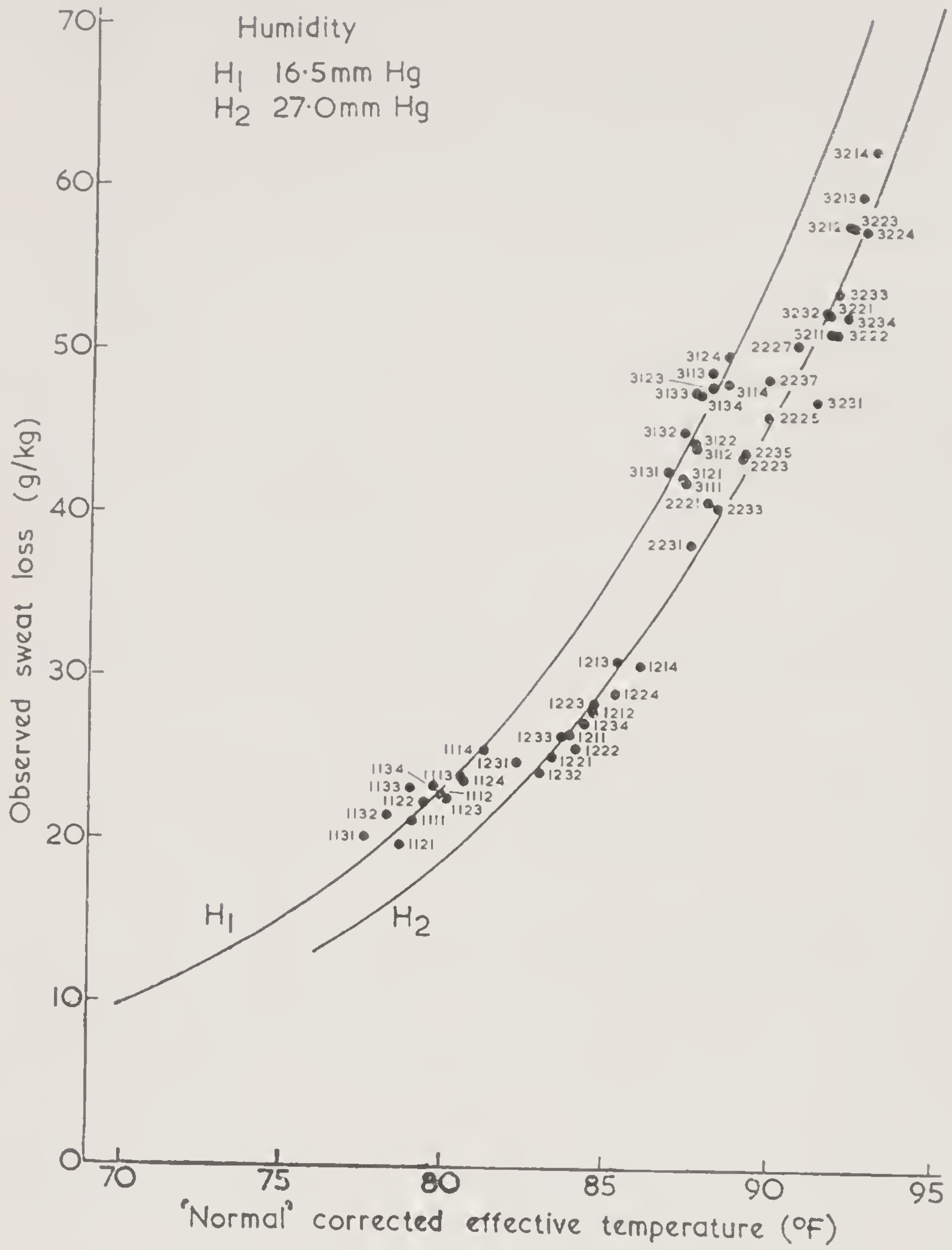

FIG. 18. Series VI & VII. The relation between observed sweat loss for men wearing overalls and 'normal' corrected effective temperature. Separate regression lines are shown for the two levels of humidity. The symbols used to identify each point are explained in the text.

It was also found empirically that if the logarithm of the sweat loss (in g/kg body weight) was plotted against effective temperature, the result was a straight line. This suggested that the relation between sweat (y) and effective temperature (x) might conform to the type

$$y = AB^x$$

which transforms into

$$\log y = \log A + x \log B$$

which may then be written as

$$\log y = a + bx.$$

There is little to choose in closeness of fit between the line represented by this equation and that given by the quadratic equation ($y = ax^2 + bx + c$), but it was considered that the use of the exponential form was preferable for there

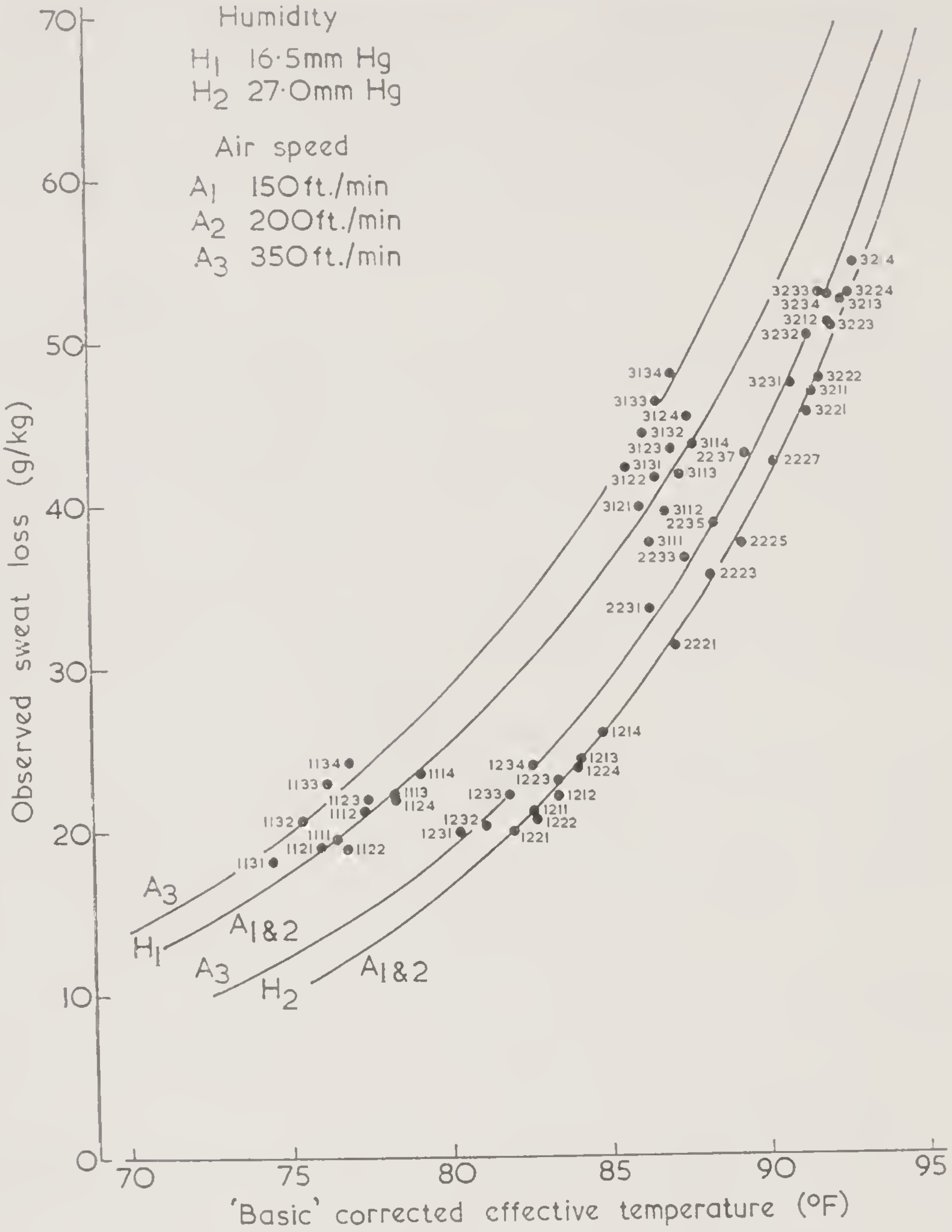

FIG. 19. Series VI & VII. The relation between observed sweat loss for men wearing shorts and 'basic' corrected effective temperature. Separate regression lines are shown for the two levels of humidity, at two levels of air speed. The symbols used to identify each point are explained in the text.

was the great advantage that the straight line relation was more amenable to statistical treatment.

The points representing sweat loss (g/kg body weight) for men wearing overalls (Fig. 18) fell along two distinct curves, the one representing the values at the lower humidity (H_1, 16·5 mm Hg), and the other the values at the higher humidity (H_2, 27·0 mm Hg). The equations for these two lines proved to be

$$\text{For } H_1,\ Y = 1{\cdot}5031 + 0{\cdot}0377(x - 83{\cdot}60)$$
$$\text{For } H_2,\ Y = 1{\cdot}5956 + 0{\cdot}0383(x - 88{\cdot}37)$$

where x is the Corrected Effective Temperature and y the logarithm of the sweat loss in g/kg body weight.

The slopes of these two lines do not differ significantly but the lines differ in position. This can be interpreted as meaning that the Effective Temperature

Scale over-estimates the effect of increasing humidity. It is preferable, however, as the value of any given effective temperature is defined in terms of the temperature of saturated air, to interpret the result as meaning that the Effective Temperature Scale over-estimates the ameliorating effect of reducing the humidity of the environment. If it were thought desirable it would be a simple matter to amend the Effective Temperature Scale to correct for this error. In this case, the addition of 2·2°F to the values of the effective temperature at the lower humidity would bring the two lines together.

The concern of this section is, however, with the adjustment of the Effective Temperature Scale for the effects of radiation, rather than the amendment of the Scale itself, so it may suffice to emphasise that the points representing the various combinations of environmental factors appear to be distributed about the appropriate regression lines independently of the level of radiant heat employed. This means that, if we accept sweat loss as a measure of physiological effect, the correction proposed by Bedford is satisfactory in the case of the 'Normal' Effective Temperature Scale.

Fig. 19 illustrates the relation between the total sweat loss (in g/kg) for men wearing shorts and the 'basic' corrected effective temperature. The appropriate regression equations, calculated as before, were as follows:

For H_1 and A_1 and A_2, $Y = 1{\cdot}4695 + 0{\cdot}0319\,(x - 82{\cdot}19)$
For H_1 and A_3, $Y = 1{\cdot}4912 + 0{\cdot}0315\,(x - 81{\cdot}03)$
For H_2 and A_1 and A_2, $Y = 1{\cdot}5348 + 0{\cdot}0404\,(x - 87{\cdot}91)$
For H_2 and A_3, $Y = 1{\cdot}5393 + 0{\cdot}0377\,(x - 86{\cdot}92)$.

Here a more complex relation is seen to hold. The results for the two levels of humidity, H_1 and H_2, are again shown to differ but, in addition, it would appear that the effects of air speed are incorrectly represented by the Effective Temperature Scale. At both levels of humidity the values at the lowest air speed (A_1, 150 ft./min) and those at the next air speed (A_2, 200 ft./min) coincide, but these are separated by an interval from the line representing the values at the highest air speed (A_3, 350 ft./min).

Arguing along lines analogous to those used in the discussion of the results at the two levels of humidity, it might be claimed that, as the Effective Temperature Scale refers to conditions in still and saturated air, the 'Basic' Scale exaggerates the ameliorating effect of increasing the air speed above 300 ft./min at these air temperatures. Such a conclusion would not, however, be entirely justified. The 'Basic' Scale was defined in terms of men 'stripped to the waist' and examination of the original papers will show that this meant wearing long trousers, shoes and socks. The experiments of Fig. 19 were performed by men wearing only shorts, and in consequence their results cannot strictly be used to provide a valid criticism of the 'Basic' Scale.

Returning, however, to the immediate question of the adequacy of the correction for elevation of mean radiant temperature, it would appear from the disposition of the points about each line that, within the existing framework of the 'Basic' Effective Temperature Scale, the correction used for variation in the mean radiant temperature is satisfactory over the range of conditions examined. This point is so important that a more adequate proof of it is desirable.

The deviations from regression for all points were therefore calculated. No completely satisfactory analysis of these results was found to be possible, and recourse was had to combining the results for shorts and overalls and analysing the results for Series VI and Series VII separately. In the case of Series VII, the effect of clothing (N) alone was significant and it may be disregarded. The important finding is that none of the effects involving added radiant heat (R) is significant. In Series VI, however, the effect of R is significant at the 1 per cent level, as is also the D × R interaction (air temperature and radiant heat) and the H × A interaction (humidity and air speed). This last may be disregarded, the important findings being those involving R.

In Table 79 are set out the mean values for the deviations from regression at the two levels of air temperature (D_1, 90°F and D_2, 110°F) and the four levels of added radiant heat (R_1–R_4). It will be seen that, though the average deviations from regression for both D_1 and D_2 are very small (0·1 g in both cases), there are differences between D_1 and D_2. At D_1 the deviation does not exceed ±0·3 g and there appears to be no systematic deviation. It may be concluded, therefore, that at D_1 (90°F) the correction for added radiant heat is quite satisfactory. At D_2 larger deviations occur: $-1{\cdot}4$ g at R_1 and 0·9 g at R_3. Again, however, there appears to be no systematic deviation; moreover, these larger values must be considered in relation to the greater amount of sweat produced at D_2.

It is considered, therefore, that, despite the fact that the deviations from regression can be shown to be statistically significant, in practice the amount of

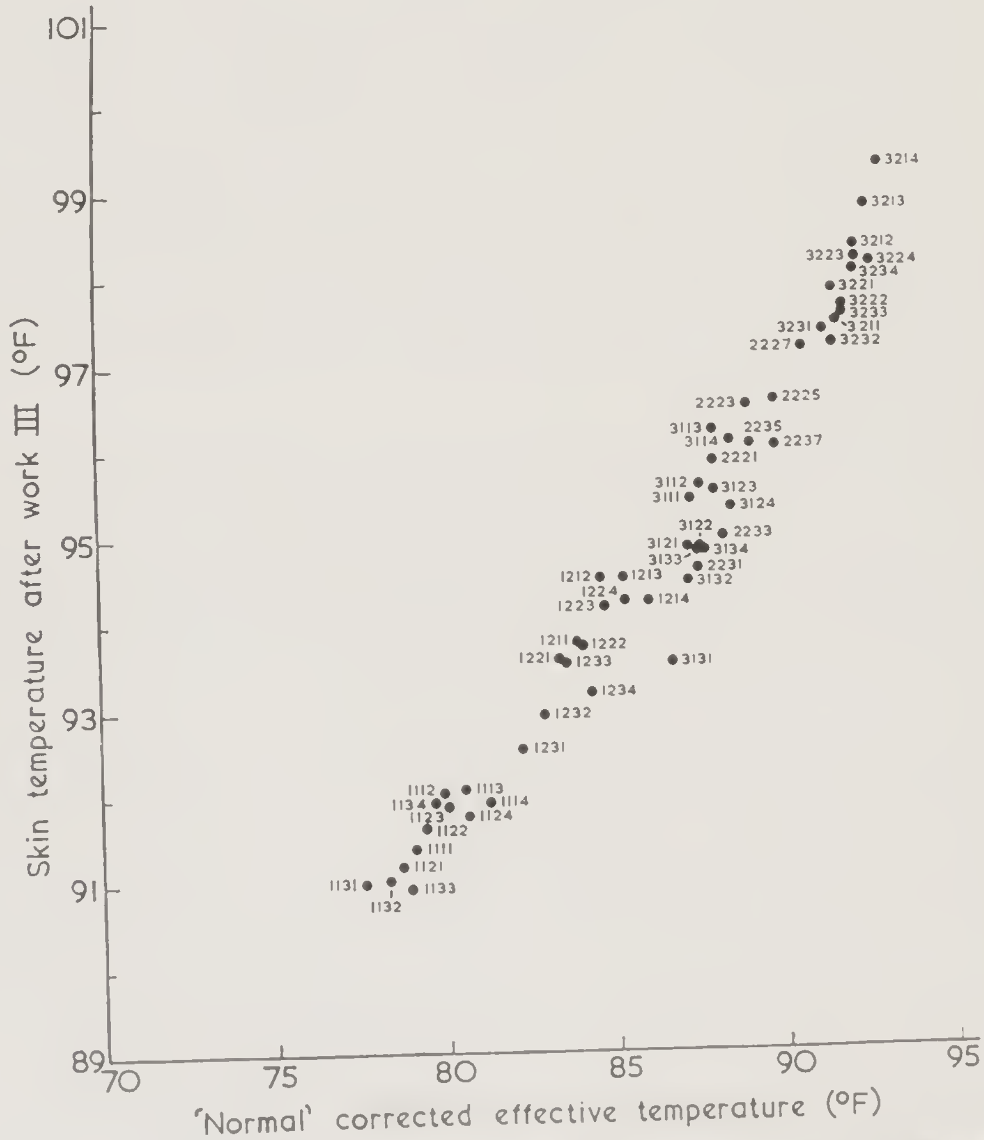

FIG. 20. Series VI & VII. The relation between mean skin temperature after the third work period for men wearing overalls and 'normal' corrected effective temperature. The symbols used to identify each point are explained in the text.

deviation is so small that it may be neglected and it may safely be said that the correction for the effects of added radiant heat is satisfactory.

Corrected effective temperature and other variates. The relation of the pulse rate and that of the rectal temperature to the Effective Temperature Scale were also examined, but in neither case was there found the clear-cut relation that had been found to exist between the sweat losses of Series VI and VII and effective temperature. Fig. 20, however, shows the very constant relation that existed between the skin temperature (in this case the mean skin temperature at the end of the third work period) and the 'normal' corrected effective temperature of the environment. (The points in this figure can again be identified by the code on p. 122.) The shape of the curve corresponds very closely to the curves obtained when sweat loss was plotted against 'normal' effective temperature (Fig. 18), but here there is only one curve and not two as in the case of sweat loss—the values for the two levels of humidity lie on the same line. From this curve it is possible, assuming the same levels of work and clothing are used, to predict fairly accurately the average skin temperature for a given 'normal' effective temperature, or, conversely, to predict with reasonable accuracy the 'normal' effective temperature, if the skin temperature is known.

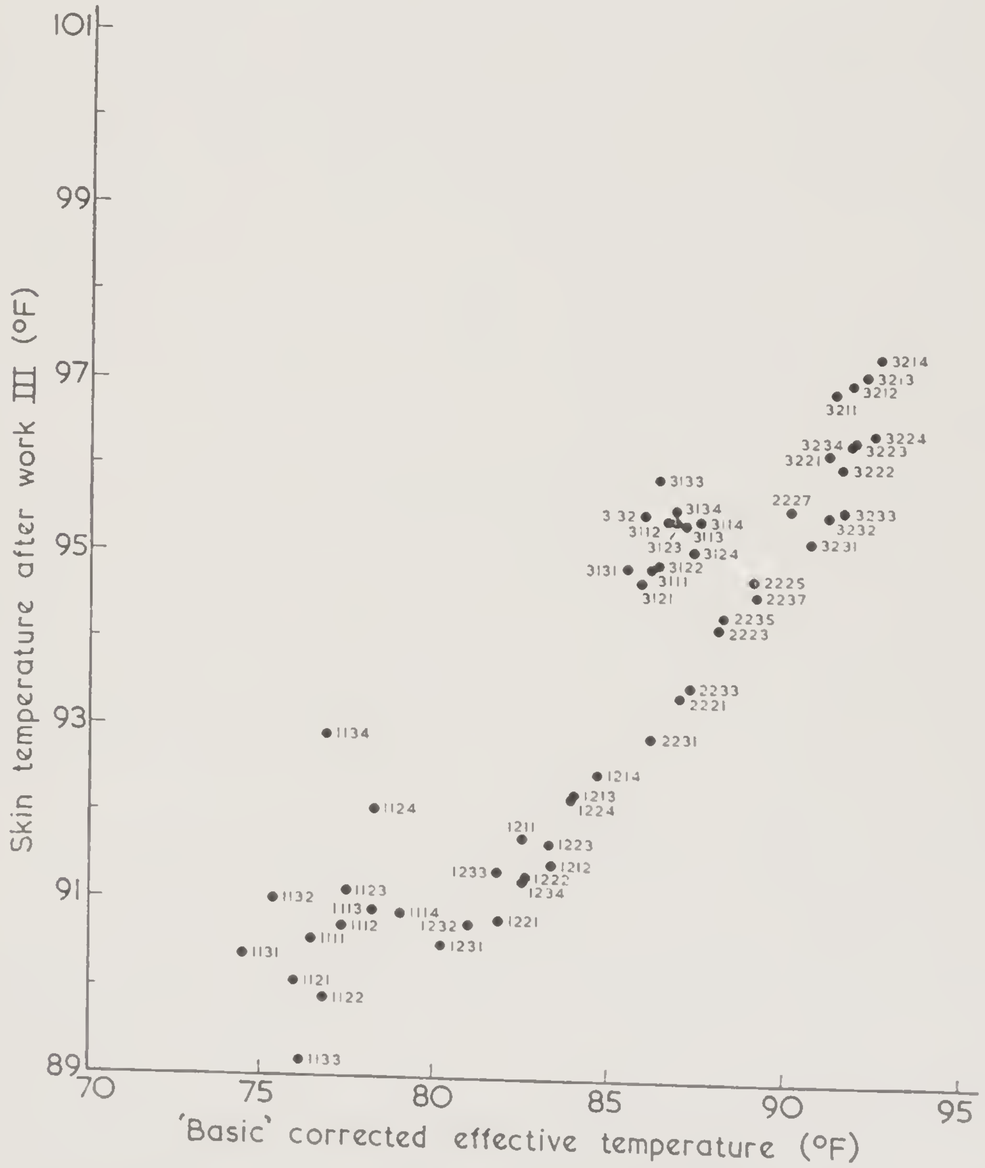

FIG. 21. Series VI & VII. The relation between mean skin temperature after the third work period for men wearing shorts and 'basic' corrected effective temperature. The symbols used to identify each point are explained in the text.

The relation between the skin temperature (at the end of the third work period) of men wearing shorts and the 'Basic' Corrected Effective Temperature Scale is shown in Fig. 21; in this case the values at the two levels of humidity lie on separate lines.

The relation between effective temperature and skin temperature was recognised very early by the original workers on the Effective Temperature Scale. In 1924 Yagloglou and McConnell showed that 'surface temperatures follow very closely the effective temperature irrespective of air velocity' and added 'the results emphasise the primary skin reactions upon which effective temperatures are based'. In 1947 Yaglou concluded that it seemed possible 'to correct the effective temperature index for humidity and possibly radiation by substituting lines of constant skin temperature for the present effective temperature lines'. He considered, however, that this correction could not be used when the air temperature exceeded 82°F, as above this point sweating may occur even in persons at rest, and, furthermore, that it could not be applied to subjects doing heavy muscular work as in this case the skin temperature drops owing to 'diversion of blood flow from the skin to the muscles'. It is of particular interest, in the light of this, that it can be demonstrated that there is a close relation between average skin temperature and effective temperature for subjects doing moderately severe work at air temperatures well above 82°F.

Careful examination of the skin temperatures recorded failed to disclose any quantitative difference in the relation between the corrected effective temperature and average skin temperature at the several levels of added radiant heat. This negative evidence can be considered to support the validity of Bedford's correction.

It is usual to distinguish between the body 'core' (the temperature of which is indicated by the rectal temperature), and an outer shell in which a temperature gradient exists from the deep core within to the skin without. The difference between skin and core temperature is largely determined by the rate of cutaneous blood flow.

Fig. 22 and 23 show, for men wearing overalls and shorts, respectively, the result of plotting the difference between the skin and rectal temperatures against the appropriate Effective Temperature Scale. That a linear relation holds is at once apparent, although in the case of shorts the two levels of humidity are separated by a wide interval. This may be taken as one further small piece of evidence in support of the claims of the devisers that the Effective Temperature Scale does provide a measure of physiological effect, and as further support for the validity of Bedford's correction for the effects of added radiant heat.

Correction of wet-bulb temperature. The method which was first used by McArdle for correcting for the effects of added radiant heat in the calculation of the P4SR was to substitute for the dry-bulb temperature the globe-thermometer reading. However, when this substitution was made, it was seen that the predicted values did not then correlate well with the observed values. It was then found empirically that if for the observed wet-bulb temperature was substituted a new value which was calculated by adding to the observed wet-bulb an amount equal to two-fifths of the difference between the air temperature and the globe-thermometer reading, the predicted values agreed well with the observed values. It is interesting to observe that this correction was devised empirically, as Vernon and Warner (1932) applied a similar correction to their wet-bulb readings when using the globe thermometer for a similar purpose, their reason being that 'it is known that if the dry-bulb temperature is raised or lowered x degrees, the wet-bulb temperature is automatically raised or lowered four-tenths of x degrees.' This is approximately true between 60°F and 70°F and 6 and 10 mm Hg vapour pressure, but is not, of course, true in general.

The fact, recognised by Vernon and Warner, that the substitution of the globe-thermometer reading for the dry-bulb reading to correct for the effect of added radiant heat results in a misinterpretation of the wet-bulb temperature is a matter of considerable importance. A simple example will serve to make this clear. At a dry-bulb temperature of 90°F and a wet-bulb temperature of 83°F, the water vapour pressure is 27·0 mm Hg and the dew point is 80·8°F. The globe-thermometer reading may be regarded as the equivalent dry-bulb

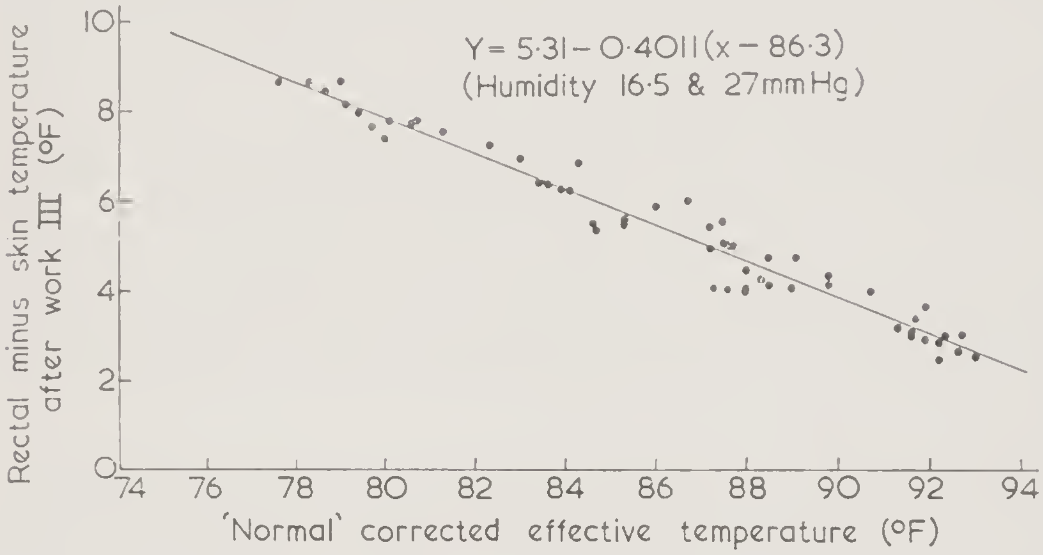

FIG. 22. Series VI & VII. The relation between 'normal' corrected effective temperature and the difference between rectal and skin temperatures after the third work period for men wearing overalls.

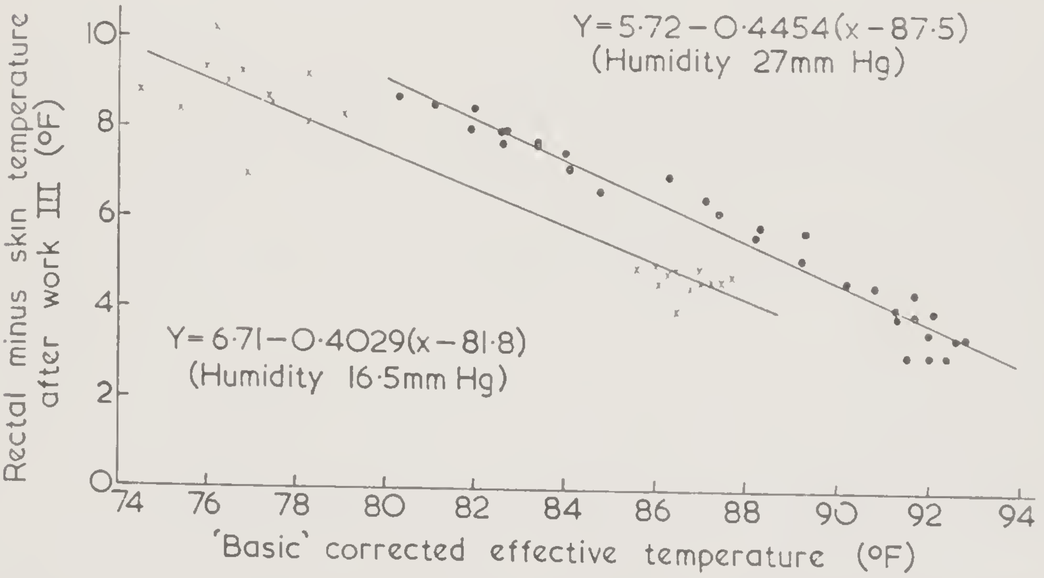

FIG. 23. Series VI & VII. The relation between 'basic' corrected effective temperature and the difference between rectal and skin temperatures after the third work period for men wearing shorts.

reading which will take into account the added radiant heat. Let us suppose that the appropriate globe-thermometer reading is 95°F. This value is then substituted for the dry-bulb temperature, or rather is now the equivalent dry-bulb temperature. The combination dry-bulb 95°F, wet-bulb 83°F, implies, as for example when used to enter the effective-temperature nomogram, that the vapour pressure is 25·5 mm Hg and the dew point is 79·3°F and that the relative humidity has been reduced from 75 per cent to 60 per cent. This would suggest that, having determined the equivalent dry-bulb temperature (globe-thermometer reading), the appropriate wet-bulb temperature to use for entering the effective-temperature nomogram is that which indicates the correct vapour pressure, or dew point, at the new equivalent dry-bulb temperature. In the example chosen, this would be 84·2°F.

Bedford purposely refrained from introducing this added complication in his correction of the Effective Temperature Scale because he considered that the degree of complexity introduced would not be justified by the greater degree of precision achieved, his scale being intended for use by those who were relatively unfamiliar with the use of psychrometric charts. Yet such a correction might be well worth while, and, indeed, many workers consider that it should be made (Yaglou, Baetjer, Machle, McConnell, Shaundy, Winslow & Witheridge, 1950).

The corrected effective temperatures were therefore re-calculated after the necessary adjustments to the wet-bulb temperatures had been made. It was then found, it must be confessed with some surprise, that the physiological findings correlated no better with these new values for the effective temperature than they did with the original values. Throughout this chapter the values of effective temperature quoted are those obtained by using the unmodified wet-bulb readings.

Radiant Heat and Upper Tolerable Levels of Warmth

The fourth of the formal aims of Series V, VI and VII was to assess the effect of increasing the mean radiant temperature of the surroundings on the upper tolerable and desirable levels of temperature and humidity (p. 97). Little direct evidence in this connection, with the exception of the findings in Series V described on page 105, has been provided. This is largely due, as was pointed out earlier, to the conflict between the requirement of a satisfactory experiment that there will be no missing values and the fact that it is impossible to determine experimentally an upper tolerable limit without exceeding it.

Although no direct evidence has been adduced on the effect on the upper tolerable levels of warmth, or indeed on the upper desirable levels of warmth, of increasing the mean radiant temperature, considerable evidence has been presented to show that the correction proposed by Bedford to the Effective Temperature Scale to embrace the effect of increasing the mean radiant temperature is valid, and that McArdle's predicted four-hourly sweat rate provides an equally reliable guide to the environmental stress of climates, both with and without an added increment of radiant heat. It may safely be concluded, therefore, that if any value on either of these scales has been shown to represent intolerable conditions for climates without added radiant heat, a climate which involves added radiant heat and has the same value on the Corrected Effective Temperature Scale, or on the P4SR scale, will also prove intolerable.

Summary

1. An account is given of the radiant heat tunnel and its use in determining the physiological effects of increasing the mean radiant temperature.

2. Three series of experiments were performed, Series V (a pilot experiment), Series VI (the definitive experiment) and Series VII (a supplementary experiment).

3. The subjects were exposed to environments in which the mean radiant temperature was raised by successive equal increments above the air temperature at combinations of various levels of air temperature, humidity, air speed and clothing.

4. The conclusions were that, over the moderate range of mean radiant temperatures examined, the physiological effects of added radiant heat were, on the whole, independent of the humidity, air speed and amount of clothing worn but did depend upon the dry-bulb temperature.

5. The finding that the amount of clothing worn was without effect was considered to apply only to the special conditions of the experiments, viz., exposure to moderate levels of mean radiant temperature for a period of four hours.

6. The finding that the effect of increasing the mean radiant temperature was dependent upon the air temperature follows directly from Stefan's Law and from the fact that the increase in mean radiant temperature was expressed as the amount by which the mean radiant temperature exceeded air temperature.

7. It was found that the P4SR nomogram predicts the sweat loss of fit acclimatized young men in hot environments in which the mean radiant temperature is above the air temperature as accurately as it predicts the sweat loss in those environments in which the mean radiant temperature is equal to the air temperature.

8. The relation between the observed sweat losses and the Effective Temperature Scale as modified by Bedford (1946) was found not to be affected by the level of mean radiant temperature. It was considered that this provided strong evidence of the validity of the modification.

9. Mean skin temperature was also shown to be closely related to the corrected effective temperature of the environment at all levels of mean radiant temperature.

10. Little direct evidence was obtained on the effect of radiant heat on the upper tolerable levels of warmth. However, the demonstration that both the P4SR nomogram and the Corrected Effective Temperature Scale satisfactorily predict the physiological effects of increasing the mean radiant temperature would indicate that the values for the upper tolerable levels of warmth determined in terms of these scales for environments in which the mean radiant temperature is equal to the air temperature also apply when the mean radiant temperature is above air temperature.

CHAPTER 7. ENERGY EXPENDITURE IN RELATION TO ENVIRONMENTAL STRESS

An account of the work of Helen M. Ferres, R. H. Fox and A. R. Lind

In the experiments at Singapore which have been described in the preceding chapters, whereas the effects of the environmental factors of temperature, humidity and air speed had been investigated at a variety of levels, the effects of only two levels of energy expenditure had been examined. The reason was that, as it had been necessary for the results obtained in Singapore to be readily comparable with those obtained in London, the levels of energy expenditure investigated in Singapore had been restricted to the two chiefly used by the workers at the National Hospital, London.

Nevertheless, as the rate of energy expenditure is one of the most important of the factors which determine the level of environmental stress, it was clearly desirable that the effects of varying the rate of energy expenditure should be examined over a wider range. This work, which is described in this chapter, was the eighth series of experiments—Series VIII—at Singapore and it has been reported in full in three papers entitled: 'The responses of four subjects walking on a treadmill at six speeds and one level of climatic stress', 'The effect of different work routines having the same total energy requirements on sweat production' and 'The energy expended by the component activities of a step-climbing routine' (Ferres, Fox & Lind, 1954*a*, *b*, *c*).

Series VIIIa: Treadmill-walking at Six Speeds and One Level of Climatic Stress

The principal aim of the first part of the series (Series VIIIa) was to investigate the physiological response, in terms of energy expenditure, sweat production, skin temperature, rectal temperature and pulse rate, of naturally acclimatized men while they were resting and while they were walking on a treadmill at each of six speeds.

Additional aims were: to determine which of the measurements provided the most accurate index of the effects of increasing thermal stress; to determine the mechanisms whereby the subjects maintained thermal balance at the climate level used with increasing rates of energy expenditure; and to examine the results in relation to various indices which predict the physiological effect of exposure to heat stress.

METHODS

Experimental Design

The effect of each of the six speeds on each of four subjects was examined twice.

As only two men could walk on the treadmill at one time, the four subjects were divided into two pairs and each pair walked on the treadmill on alternate days.* The order in which the six speeds were used in the first half of the series of experiments was randomized separately for each experiment and the side of the treadmill on which each member of the pair walked was determined by lot for each experiment. In the second half, which was a duplicate set of experiments, the order in which the speeds were used for each pair and the positions on the treadmill were reversed.

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* On the intervening days the pairs performed a step-climbing routine in the climatic chamber. The measurements obtained are not reported here.

Environmental Conditions

Only one climate was used throughout these experiments—dry-bulb temperature 90°F, wet-bulb 80°F, and air speed 300 ft./min. The combination of these dry-bulb and wet-bulb temperatures corresponded to an absolute humidity of 23·5 mm Hg and a relative humidity of 65 per cent. The walls were maintained at air temperature so that the mean radiant temperature remained constant and may be considered to have been the same as the air temperature.

The adoption of a climate with a low heat stress made the investigation of relatively high work rates possible and increased the chance of completing the experimental programme without 'spoiled' experiments. The thermal stress of this climate, as judged by the 'Normal' Effective Temperature Scale, was believed to be slightly less than the average daily maximum that a person resident in Singapore would experience at the time of the experiments; it was hoped that the use of this climate would thus eliminate, or reduce to a minimum, acclimatization changes resulting from the experimental procedure and provide data that would be applicable to residents in Singapore. The low level of absolute humidity chosen was expected to ensure total evaporation of sweat.

Subjects

The subjects were four volunteers from army units in Malaya. Their physical characteristics were:

Subject	*Age (years)*	*Height (cm)*	*Weight (kg)*	*Surface area (m^2)*
P	23	175·8	69·59	1·849
M	23	177·1	71·10	1·876
B	19	162·5	67·76	1·728
W	21	162·0	61·66	1·655

On the basis of similarity of these characteristics, P and M were chosen to constitute one pair of subjects and B and W the other.

Experimental Procedure

The experimental routine used and the times at which the various measurements were made during the experimental period are set out in Fig. 24.

The method of 'working' used in these experiments was walking on a horizontal treadmill at one of six speeds—2·0, 2·4, 2·8, 3·2, 3·6 and 4·0 m.p.h. When resting, the subjects sat on wooden stools without backrests.

Energy expenditure was measured by an open-circuit technique employing Douglas bags and analysis of samples of expired air using a Haldane gas-analysis apparatus. The sweat losses were estimated by weighing. Before entering the chamber each subject drank 500 ml. of water and a further 500 ml. were drunk immediately prior to the work period. The temperature of the water was recorded.

Skin temperatures were measured (using copper-constantan thermocouples as described in Chapter 5) at the following sites—forehead, index finger, forearm, upper arm, chest (above nipple), mid-abdomen, mid-dorsal region of the back, and mid-point of the lateral aspect of the thigh. The order of application to the eight sites was randomized for each set of measurements in every experiment.

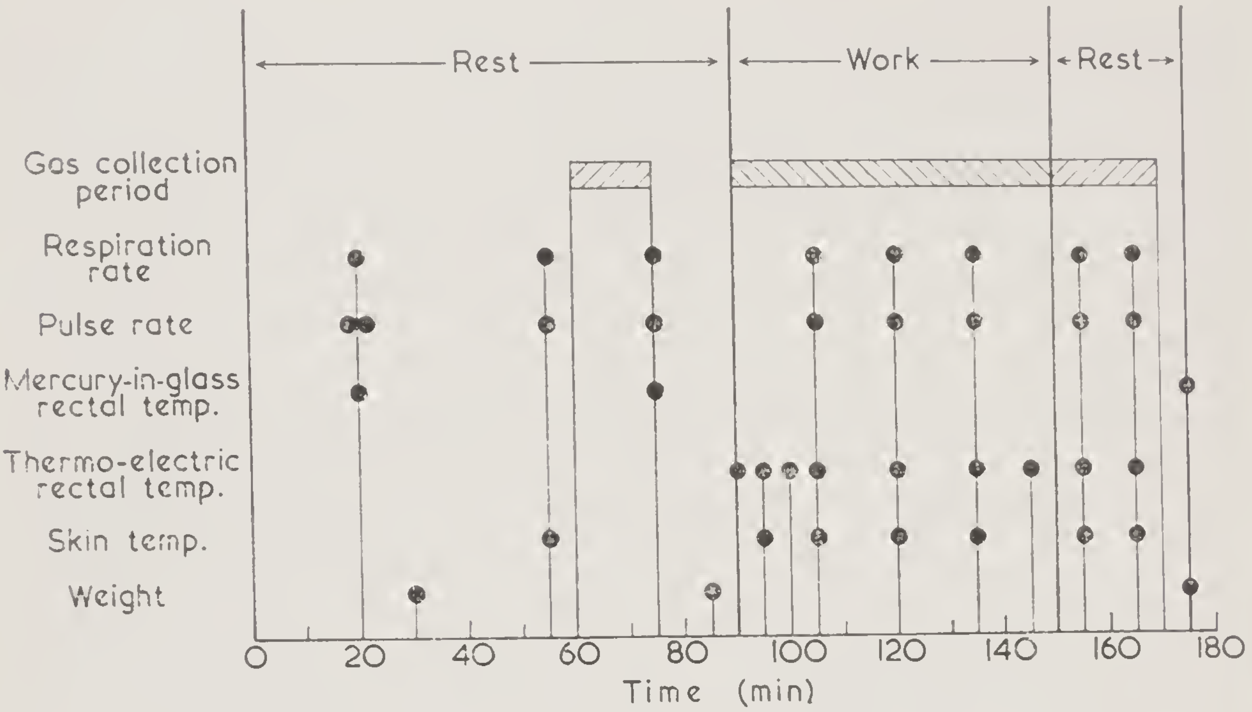

FIG. 24. Series VIIIa. Experimental routine used in determining the physiological effects of treadmill-walking at various speeds.

Rectal temperature measurements were recorded while the subjects were working and also in the immediate post-work period, using a thermo-electric rectal thermometer. Additional measurements before and after the work period were made using mercury-in-glass rectal thermometers.

Measurements could not be made on two subjects simultaneously so the second subject of each pair carried out the same routine as the first but began and ended each item 5 min after the first subject.

The resting activity and posture were closely controlled. The subjects either talked or read. Heated arguments or animated conversation with gesticulation were not allowed. The usual posture adopted was leaning the body somewhat forward with the elbows propped on the thighs. When walking, the subject could place one, but not both, of his hands on a convenient bar across the front end of the treadmill. The two subjects in each pair always walked in step of their own accord.

RESULTS

Terminology

The following terms were adopted in the analyses of variance to describe the sources of variation:

Subject. Denoted by the initial P, M, B or W. The term 'subject pair' refers to the combined effects of the pair P and M or the pair B and W.

Speed. The effect of increasing the walking speed of the subjects.

Time. The difference between results recorded during the first half of the series of experiments and those recorded during the second half.

Stage. The phase in the experimental routine at which a measurement was made, denoted by the time, in minutes, from the beginning of the experiment (Fig. 24).

The terms 'net walking energy expenditure' and 'net walking sweat loss' refer to the values obtained after subtracting the appropriate resting values from the working values.

The Effect of the Experimental Climate

It was hoped that the climate chosen for these experiments would obviate changes in the physiological responses of the subjects caused by an increase in their level of acclimatization. In Fig. 25 the climatic stress in Singapore at the time of the experiments, as measured by the 'Normal' Effective Temperature Scale, is compared with that of the experimental climate. The effective temperature values of the Singapore climate were calculated from observations made by the Malayan Meteorological Service at Kallang Airport, Singapore.

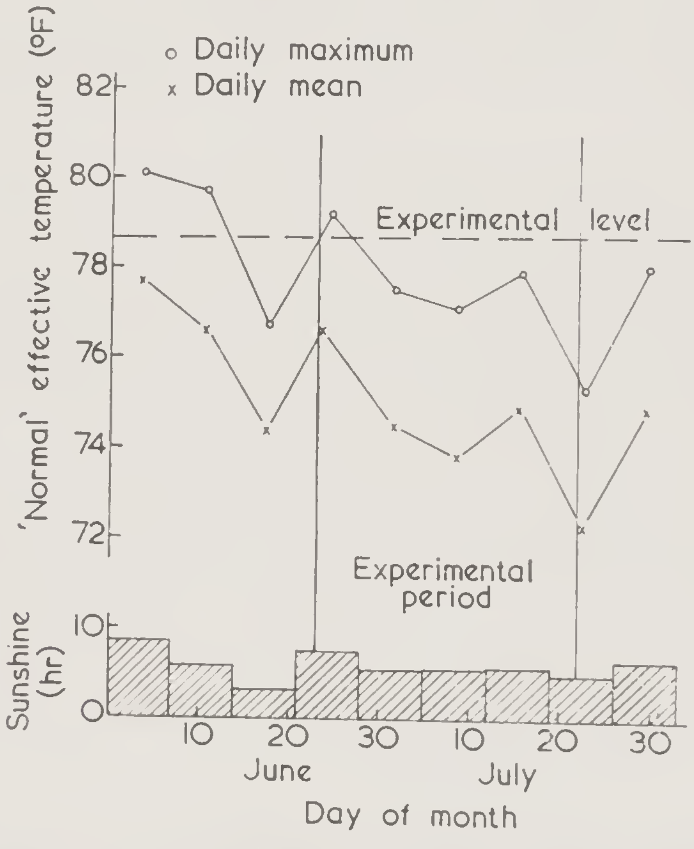

FIG. 25. Series VIIIa. Average weekly values of effective temperature and of hours of sunshine per day in Singapore, June-July, 1952, and the effective temperature of the experimental climate.

There was a decrease in the thermal stress of the Singapore climate between June and July, so that the stress of the experimental climate was above that of the ambient conditions in July but about the same in June. The effective temperature values for the Singapore climate do not, however, make any allowance for the considerable additional burden of radiant heat caused by exposure to the sun and, moreover, the air speeds at Kallang Airport were considerably higher than those generally experienced elsewhere in Singapore. It would seem safe to conclude that the thermal stress of the climate adopted in this series of experiments was of the same order as that experienced under conditions of normal residence in Singapore and would not have increased the natural level of acclimatization of the subjects.

Resting Energy Expenditure and Sweat Loss

The mean values for the twelve estimates of resting energy expenditure and resting sweat loss for each subject are given in Table 80, together with the same values expressed in relation to body weight and surface area. It is clear that the differences between these four subjects in their rate of resting energy expenditure and resting sweat loss were not removed by allowing for their differences in body size. M was especially notable in having the lowest resting energy expenditure and the lowest resting sweat loss of the four subjects, although he was the heaviest subject and had the greatest body surface area.

Inspection of the individual values for resting sweat loss and energy expenditure suggested that on days on which a subject exhibited a high or a low resting energy expenditure the sweat loss was similarly affected. After eliminating subject differences the regression equation is

$$Y = -46{\cdot}6 + 1{\cdot}839x$$

where y is the resting sweat loss in g/hr and x the resting energy expenditure in kcal/hr. The linear coefficient, 'b', is significant at the 1 per cent level. It is therefore possible to predict the resting sweat loss for any resting energy expenditure. Similarly, the resting energy expenditure may be predicted from the resting sweat loss.

Working Energy Expenditure and Sweat Loss

The mean net walking energy expenditure and the mean net walking sweat loss for each of the four subjects, at six different speeds and with two replications for each speed, are shown in Table 81. Figs. 26 and 27 show, respectively, the mean net walking energy expenditure and mean net walking sweat loss of the two replications for each subject separately at each speed.

Inspection of the values for the energy expended on work (Table 81) shows that expressing the values per unit of body weight or surface area almost removed the differences between P, B and W. M was the heaviest, with the greatest surface area of the four, and he expended significantly less energy than

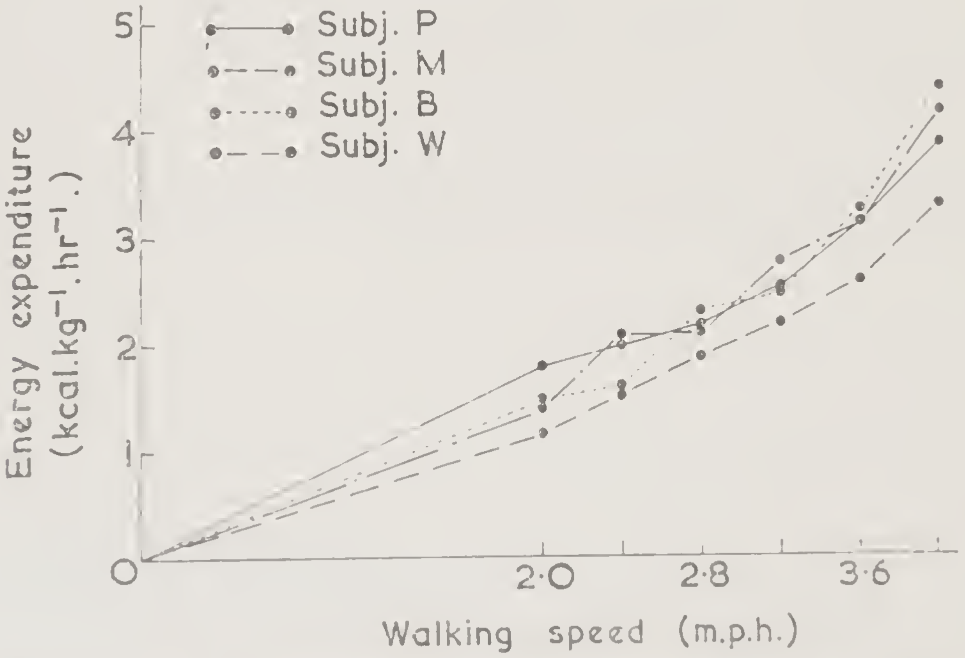

FIG. 26. Series VIIIa. Net walking energy expenditure (total metabolism minus resting metabolism). Mean values for each subject at each speed.

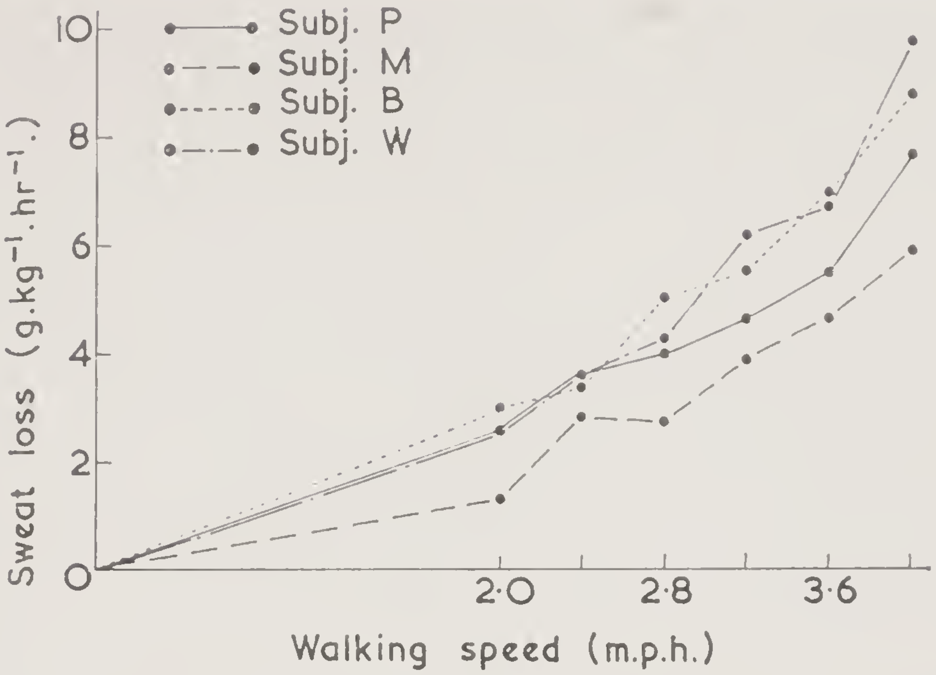

FIG. 27. Series VIIIa. Net walking sweat loss (total loss minus resting loss). Mean values for each subject at each speed.

the other subjects, so that the differences between him and the other three were increased. It should also be noted that M had a significantly lower sweat loss than any of the other subjects.

Working energy expenditure. To examine the net walking energy expenditure more closely, the individual values were submitted to analyses of variance. A summary of the significant effects and appropriate mean values is shown in Table 82.

M expended significantly less energy than the others, and W had a lower energy expenditure than P or B. Dividing the energy expended by body weight removed the significant differences between W, P and B, but since M was the heaviest of the four subjects the differences between him and the other three were increased.

For each increase of 0·4 m.p.h. in the rate of walking there was a significant rise in the level of energy expended by both pairs of subjects, with one exception —for the subject pair PM between 2·4 and 2·8 m.p.h.

It will be noted that no significant change in energy expenditure with time was found for either pair of subjects when the results of the first half of the series of experiments were compared with those of the second half. Thus any decline in the energy expended on walking during the series of experiments due to training was negligible.

The other significant finding suggests that the changes in B's energy expenditure with increasing speed differed from those of W. Inspection of the individual values showed, however, that this was due to causes outside the experiment.

Working sweat loss. A summary of the significant effects and the appropriate mean values is set out in Table 83.

On comparing the values for the mean net walking sweat loss (Table 83) for the individual subjects, M was found to have sweated significantly less than W, P and B, and this difference was not removed when the values were expressed per kilogram of body weight, although the difference between B and W was removed. It can be seen that sweat production closely reflected the subject differences already noted for energy expenditure. There was one difference; when the sweat production was expressed in terms of body weight P sweated significantly less than B and W.

An important difference between the results of the analyses of variance of energy expenditure and of sweat loss was the significant change in sweat production, but not in energy expenditure, with time. Examination of the subjects' mean sweat loss values at the middle and at the end of the series of experiments showed that this increase with time was caused by an increase in sweat production by the pair PM; there was a decrease by the pair BW. Within the subject pairs, B changed more than W and M more than P. This result cannot be attributed to a training effect resulting in an altered energy expenditure since a significant change in energy expenditure did not occur.

For each increase of 0·4 m.p.h. in the rate of walking there was a significant rise in the sweat production of both pairs of subjects, with one exception; for the pair PM there was no significant difference between the sweat losses at 2·4 and 2·8 m.p.h. This corresponded with the absence, already noted, of a significant change in energy expenditure over this speed interval for the same pair.

The difference between B and W in the rate of change in sweat production with increasing walking speed probably reflected their differences in energy expenditure. When the results from the analyses of variance of working energy expenditure and sweat loss were compared, it was clear that sweat production had very closely reflected the energy expenditure of each subject. In order to examine the relation between energy expenditure and sweat production more closely, the individual values for net walking sweat loss were expressed in relation to net energy expenditure (g/kcal), and the resulting values were submitted to analysis of variance. Appropriate mean values for the significant effects are given in Table 84.

The analyses showed that within each pair the members did not differ significantly in net walking sweat loss per kcal of energy expended. The values for the pair BW, however, did differ significantly from those for the pair PM.

The significant effect with speed for the subject pair PM was caused by the unexpectedly low value at 2·0 m.p.h. walking speed, and does not provide evidence of a consistent change in the relation between sweat loss and energy expenditure.

It was expected that the results of the analyses of net walking energy expenditure and sweat loss would show that the effect of time had been significant. The analyses showed that this effect just failed to reach the level of significance, and it is assumed that this was because there had been insufficient observations.

Pulse Rate

Analyses of variance were performed on the values for the pulse rate at three stages during the work period (105, 120 and 135 min from the beginning of the experiment). A summary of the significant effects and the appropriate mean values is set out in Table 85.

The pulse rates of P and B were significantly higher than those of M and W during the work period. As the walking speed increased, the pulse rates of both pairs of subjects also increased, but the effect was less consistent over each speed interval than the sweat loss response. No change with time was found in the pulse rates of the subjects when the first half of the series of experiments was compared with the second. The pulse rates did not differ significantly at the three stages in the work period. The significant interactions between stage and speed for P and M and subject and speed for B and W are of no real interest.

Skin Temperature

The skin temperatures of the subjects were measured once before the work period, four times during work and twice during the recovery period following work (Fig. 28). The mean values for all four subjects before work were remarkably close. They fell two to three degrees after 15 minutes of work but when measured again 30 and 45 minutes after starting work they showed little further change. Fifteen minutes after the work period ended, skin temperatures had risen to approximately 0·5°F below their original resting values.

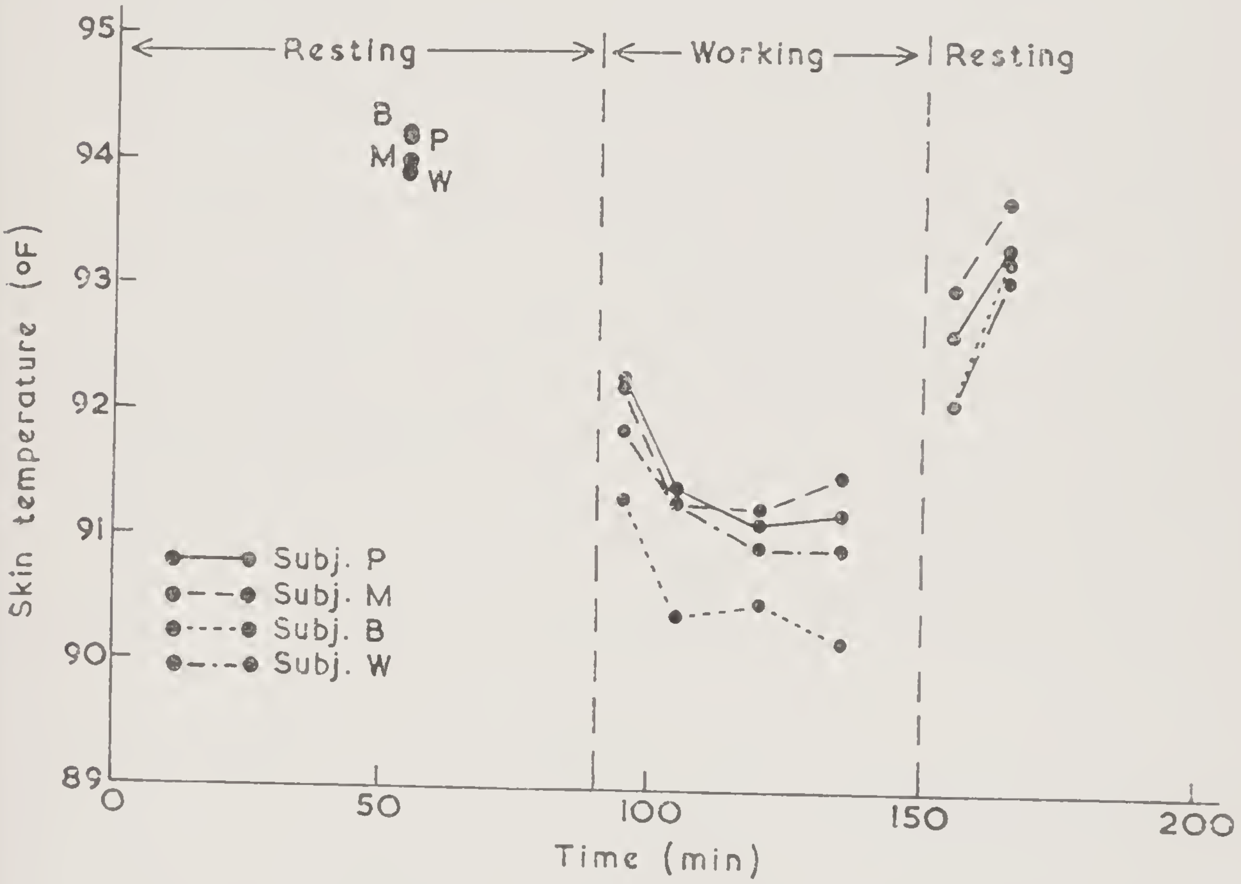

FIG. 28. Series VIIIa. Change in skin temperature of each subject throughout the experimental period. Mean values for all walking speeds.

The measurements after 15 and 30 minutes' work and 5 and 15 minutes after work had ended were submitted to analyses of variance. A summary of the significant effects and appropriate mean values is given in Table 86.

B had a significantly lower skin temperature than the other three subjects during work, and when the working and post-work values were combined his skin temperature was shown to have been significantly lower over the whole period than that of M and P.

An increase in the rate of walking produced a significant decrease in skin temperatures for both pairs of subjects, but the effect was small and the decrease with increase of speed was not linear.

In the two post-work measurements the effect of the walking speed became progressively less marked. There was also some evidence that for the PM pair the effect of walking speed produced a more marked change in skin temperature in the measurements at 15 and 30 minutes after work commenced than after 45 minutes' working.

The only significant change in skin temperature with time was caused by P whose skin temperature was slightly higher in the first than in the second half of the series of experiments.

Rectal Temperature

Thermo-electric rectal temperature measurements were recorded at seven stages during the work period and twice in the first 15 minutes after work had ended (see Fig. 24). The first two measurements recorded after work had commenced were not analysed since there was evidence that the rectal thermocouple elements had not reached thermal equilibrium with the rectum. The remaining values were submitted to analyses of variance and a summary of the results is presented in Table 87. The measurements are shown graphically in Fig. 29, which also shows the readings made before and after the work period from mercury-in-glass thermometers.

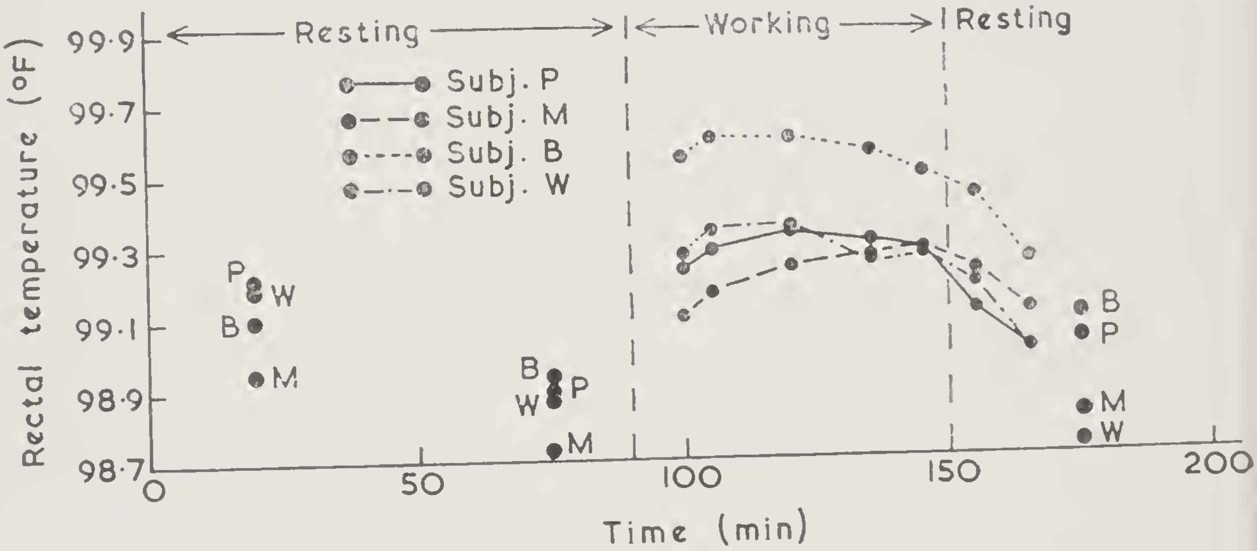

FIG. 29. Series VIIIa. Change in rectal temperature of each subject throughout the experimental period. Mean values for all walking speeds.

B differed significantly from the other three subjects in having a higher rectal temperature while working.

An increase in the rate of walking caused a significant rise in rectal temperature, but the effect was variable and apparently largely swamped by the day-to-day variations in rectal temperature. The significant effect of 'stage' showed that rectal temperatures had begun to fall before the work period ended. Within 15 minutes of ending work, rectal temperatures for both pairs were below those recorded 15 minutes after commencing work.

A significant difference between the responses of M and P at different stages is of interest; the rectal temperature of M continued to rise until the last measurement during the work period, whereas for P a fall in rectal temperature commenced after 30 minutes of work. Moreover, M's rectal temperature was below P's at the first measurement but by the end of the work period they were the same. This indicates a greater storage of heat by M than by P.

B and W had a significantly greater increase in rectal temperature during the work period in the second than in the first half of the experiments.

Energy Expenditure per Mile Walked

Each value for net walking energy expenditure per kilogram of body weight per hour was divided by the distance walked per hour, and the results were submitted to an analysis of variance. A summary of the significant effects and the appropriate mean values is set out in Table 88.

There was no significant difference in the energy expended by P, B and W, but M expended almost 19 per cent less energy per kilogram body weight per mile walked than they did.

The energy expenditure per kilogram body weight per mile walked increased slightly as the walking speed increased from 2·0 to 3·6 m.p.h., and more markedly as it increased from 3·6 to 4·0 m.p.h.

Characteristics of the Subjects' Gaits

It was considered possible that the much lower energy expenditure of one subject while walking might have been caused by a difference in gait, as there did appear to be some difference between the subjects in the amount of vertical body movement and the length of stride taken. An experiment was therefore carried out to measure these two characteristics of each subject's gait at each of the six speeds.

The amount of vertical body movement was measured by an observer who stood at a fixed distance in front of the subject while the latter was walking on the treadmill alone and estimated, by means of a vertical scale at a fixed distance behind the subject, the average rise and fall of a marker placed on the subject's head. In order to determine the length of stride, the number of steps taken in one minute was counted at each walking speed. It was found that although M took the shortest stride and had the least vertical body movement, there were also differences in these characteristics among the other three subjects who differed little from each other in their energy expenditure during walking.

Observed Sweat Loss and the P4SR Index

In general, it is not valid to compare observed sweat losses over short periods with those predicted by the P4SR Index, since at high levels of thermal stress the sweat rate alters during a four-hour period of exposure; however, these experiments were performed at a comparatively low thermal stress and such a comparison is thought to have some value in this case. The observed hourly sweat losses multiplied by four were therefore compared with the P4SR values for the appropriate energy expenditure levels at each walking speed for each subject. In every instance the corrected observed sweat loss values were found to exceed the P4SR values, and in Table 89 are shown the differences when the predicted values were subtracted from the observed.

The values shown in Table 89 were submitted to an analysis of variance and the effect of speed was not found to be significant, but the mean values for P and M were significantly lower than those for B and W.

Thermal Exchange Analysis

The experiments were so designed that the results for the 80 min period between 90 and 170 min (the working period of 60 min and most of the subsequent resting period) could be submitted to a thermal-exchange analysis. The British Thermal Unit was adopted as the unit of heat in the analyses, firstly because temperatures were measured on the Fahrenheit scale, and secondly, because it was desired to make the results readily comparable with those of Haines and Hatch (1952). To reduce the effect of variability only four estimates were made; these were the means of the three higher and the three lower walking speeds for each of the two pairs of subjects.

The heat gain by metabolism (M) was calculated from the gaseous exchange during the resting and recovery period in the usual way. The heat loss by evaporation (E) was calculated by correcting the loss of body weight for the weight loss due to metabolism and then by dividing it into that due to evaporation of sweat alone (E_1) and that due to evaporative heat loss in the lungs (E_2).

Heat exchange through respiration can occur by warming or cooling the inspired air and by evaporation or condensation of moisture in the respiratory tract. In this case the air was very nearly at body temperature so that the heat lost by warming the air could be neglected. The heat loss by evaporation could be determined with reasonable accuracy as the moisture content of the inspired air was known and as it was observed that, whereas condensation did not occur in the respiratory tubing within the chamber, it did occur just outside the chamber where the temperature was only a few degrees lower.

Heat storage (S) was calculated by using the mercury-in-glass rectal temperature measurements and skin temperature measurements made just before and just after the reference period, and by assuming a 1 : 2 relation of skin to deep-body-tissue weights. Correction was made for the effect of drinking 500 ml. of water about 19°C (34°F) below body temperature during the reference period. This is equivalent to about 34 B.Th.U.

Heat exchange by convection (C) was calculated using the formula of Haines and Hatch (1952)

$$C = 0{\cdot}11\sqrt{V} \times A(t_s - t_a)$$

where C is the rate of convective heat loss (B.Th.U./hr); V is the air speed (ft./min); A the surface area of the body (sq. ft.); and t_s and t_a the skin and air temperature (°F). Convective heat losses for the work period and the post-work period were calculated separately. In these experiments the heat loss by conduction (Cn) was negligible.

Heat exchange by radiation (R) was calculated from the formula (Haines and Hatch, 1952)

$$R = eKA_r(T_w^3 + T_w^2T_s + T_wT_s^2 + T_s^3)\,(t_w - t_s)$$

where R is the rate of heat loss by radiation in B.Th.U./hr; K is the universal radiation constant ($1{\cdot}73 \times 10^{-9}$ B.Th.U./hr/ft.^{2}/°F); A_r is the effective radiation area of the body in sq. ft. (approximately 0·8 times the DuBois surface area); e is the emissivity of the body which may be taken as unity; T_w and T_s are the mean radiant temperatures of the surroundings and the average skin temperature in °F (absolute); and t_w and t_s are the mean radiant temperature and skin temperature in °F. The radiation heat losses were separately calculated for the working and recovery periods.

The maximum evaporative heat loss—'E_{max}' of Haines and Hatch (1952)—was calculated from their formula

$$E_{max} = 0{\cdot}53AV^{0{\cdot}37}(P_s - P_a)$$

where E_{max} is the maximum rate of heat loss (B.Th.U./hr) by evaporation of sweat when the nude body surface is completely wetted by sweat; A is the body surface area (sq. ft.); V is the air velocity (ft./min) and P_s and P_a are the vapour pressure of water at the temperature of the skin and of the air (mm Hg). The results are summarized in Tables 90 and 91.

DISCUSSION

The rate of energy expenditure is an important factor in determining the response of an individual exposed to a hot environment; it is essential, therefore, that in experiments intended to measure the stress of such environments it should be susceptible to accurate control and measurement. Direct measurement of the energy expenditure throughout an experiment is seldom made on account of the tedious and time-consuming nature of the techniques required which may, in themselves, alter the response of the subjects to the experimental heat load. It is rather the custom to give the subjects standardized exercises to perform throughout the experimental period and to assume that, with accurate control of the rate of working and time spent at each level of activity, the energy expenditure of the routine will be constant for all individuals and under all conditions. It becomes of importance, therefore, to determine to what extent this assumption is correct.

Energy Expenditure: Walking Subjects

It is generally accepted that, in any physical activity in which a large proportion of the energy expended is used to move the body, the energy expenditure will be influenced by the body weight. It is considered (Benedict & Murschhauser, 1915; Erickson, Simonson, Taylor, Alexander & Keys, 1946; Keys, 1949) that the energy expended during walking should be expressed in direct proportion to body weight, and this relation has been accepted by the Committee on Calorie Requirements of the Food and Agricultural Organization of the United Nations (1950), although recently Mahadeva, Passmore and Woolf (1953) obtained a somewhat different relation from a detailed study on fifty subjects.

In Table 81 the energy expended while walking by each of the four subjects expressed in relation to their respective body weights is compared with their total energy expenditure. It is clear that expressing the energy expended as a function of body weight has markedly reduced the subject differences between three of the four subjects. The fourth subject (M) differed greatly from the other three; he was the largest of the four subjects and, since he also had the lowest total energy expenditure, expressing the net energy expended on walking per unit of body weight served only to increase the difference between him and the others.

Large differences between individuals in the energy expended on standardized tasks, even after allowing for the influence of body size, have been reported before. In 1915 Benedict and Murschhauser, summarizing the findings of earlier workers who had measured the calories expended on walking per horizontal kilogram metre, concluded 'In general when the rate of walking does not exceed 80–90 metres per minute, the values lie between 0·3 and 0·7 gram calories with a distinct tendency for them to approach 0·55 gram calories'.

If it were possible to relate variations of this nature to measureable differences in the gaits of subjects, or to some physical difference, it might prove possible to avoid the necessity for direct measurement of energy expenditure in climatic experiments by selecting suitable subjects. M appeared to walk in the same way as the other three subjects, but measurements showed that when walking naturally he took shorter and therefore quicker strides than the others and exhibited less vertical body movement. There were, however, differences in these characteristics of gait between the other three subjects whose net energy expenditure per kilogram body weight agreed closely, and it is concluded, therefore, that although M's gait was probably partly responsible for his greater economy of energy while walking, no direct relation between the gait and energy expenditure of these subjects could be identified. In climatic physiology experiments the number of subjects that can be investigated in any one series is often very limited, and it is therefore advisable to determine the level of energy expenditure characteristic of each subject.

The day-to-day variations in the energy expenditure of each subject were comparatively small. As the effect on physiological responses of such variations would also be small, it is unnecessary to measure the energy expenditure at each exposure in a series of experiments. It must be established, however, that differences in the levels of environmental stress to be investigated at the different exposures will not themselves alter the level of energy expenditure characteristic of each subject.

It is desirable that, in the method used to 'work' subjects, the energy expended should bear a simple, preferably linear, relation to the work done. It has been shown that for the subjects of the experiments just described, the relation between walking speed and energy expended was almost linear between 2·0 and 3·6 m.p.h. At 4·0 m.p.h., walking required a disproportionate increase in the energy expended per mile walked, and at speeds much in excess of this walking became unnatural. To increase the range of energy expenditure which can be investigated with this method of 'working', and at the same time retain a simple relation between work rate and energy expended, it would be necessary to resort to the use of either load-carrying while walking or walking on an inclined grade. Each of these methods has its drawbacks and so it must be concluded that although the use of walking is excellent when it is desired to control energy expenditure in the low and medium ranges, it is less suitable when the effects of high levels of energy expenditure are to be examined.

It had been suggested from time to time that one outcome of acclimatization to hot climatic conditions might be a reduction in the energy expended on work. The present results were therefore compared with those from subjects measured in temperate climates. Benedict and Murschhauser (1915) concluded that the energy expended in walking in such climates was about 0·55 gram calories per horizontal kilogram metre. The mean values for our subjects while walking at 2·8 and 3·2 m.p.h. (corrected for oxygen debts, and with appropriate allowances for weights of clothing and equipment) were 0·49 cal for the mean of subjects P, B and W, and 0·43 cal for subject M. These values fall well within the range of 0·3–0·7 cal given by Benedict and Murschhauser.

Mahadeva *et al.* (1953) measured the energy expended by fifty subjects walking at 3·0 m.p.h. on a treadmill and obtained the regression equation

$$C = 10{\cdot}24 + 0{\cdot}47W \pm 3{\cdot}67$$

where C is the gross energy expenditure in kcal in 10 min, W is the gross body weight in kg, and the last term is the standard error of estimate. In Table 92 the mean values for the subjects walking at 2·8 and 3·2 m.p.h. (corrected for oxygen debts and weights of clothing and equipment) are compared with the values for walking at 3·0 m.p.h. predicted by this equation. This comparison shows that in three of the four subjects, P, B and W, the energy expended agreed well with the predicted values for subjects living in temperate climates. The fourth subject, M, exhibited a lower energy expenditure; this was probably a natural characteristic rather than an effect of climate.

Energy Expenditure: Resting Subjects

In climatic physiology experiments, a rest period must fulfil two requirements which are not easily reconciled. It must provide a change and relaxation from working and yet ensure a satisfactory degree of control of the rate of energy expenditure.

In the experiments just described it was observed that the restlessness of the subjects varied considerably from day to day, but—somewhat surprisingly—that the variation in their measured resting energy expenditure was small. The explanation is that a large part of the energy expended while resting is to be attributed to the relatively constant basal metabolic processes of the body. The energy expended above the basal rate can be sub-divided into that required to maintain the body in a sitting posture and that expended on the voluntary movements of restlessness. This suggests that any reduction in the differences in energy expenditure that would result from strictly controlling the posture and voluntary activities of subjects while resting would be relatively small. The comparatively small day-to-day variations did, however, influence the sweat loss; on days on which the energy expenditure was unusually high or low the sweat loss was similarly affected.

Differences between the subjects' resting energy expenditure levels are not removed by expressing the values in terms of body size (Table 80). Moreover, B, the subject with the highest mean resting energy expenditure level, also had the highest day-to-day variability, and M, the subject with the lowest resting energy expenditure, the least variability. From these results it would seem that the level of resting energy expenditure is not related directly to the size of the subject or his predicted basal metabolic rate, but in part reflects his characteristic level of restlessness. Furthermore, although it seems likely that on exposure to a high level of environmental thermal stress this voluntary expenditure of energy would be reduced, the magnitude of such a reduction would not be expected to be very great. The finding that M, who had the lowest energy expenditure while walking, also had the lowest resting energy expenditure would indicate that although M's characteristic gait may have played some part in his economy of energy while walking it was not the only factor concerned—there was presumably some other factor which was common to both walking and resting.

It is concluded that the mean resting energy expenditure exhibited by each subject could not have been predicted accurately and that, as with the working expenditure, the characteristic level for every subject must be measured and the effect on it of varying the level of the climatic stress determined.

Climate and Heat Loss

The experimental climate (dry-bulb 90 F, wet-bulb 80 F and air speed 300 ft./min) was, in general, close to the maximum level of the Singapore climate, although, as Fig. 25 shows, this varied from day to day and from week to week. These experiments serve, therefore, to illustrate the importance of the level of activity in determining the physiological strain experienced by those who live in a climate similar to that of Singapore. A change in the level of activity from sitting to walking at 4·0 m.p.h. produced a four- to five-fold increase in sweat production. In such a climate, a man seated and clad only in shorts is able to lose by means other than the evaporation of sweat an appreciable proportion of the metabolic heat produced. When he is walking at about 4·0 m.p.h., sweating cools the skin, reducing the heat lost by radiation and convection, so that almost all the heat metabolism must be dissipated by evaporative cooling.

Endurance of High Levels of Stress

Although these experiments were not designed to provide direct information about the upper tolerable limits of heat, one of the results is relevant to the factors which influence ability to endure high levels of stress. It will be remembered that subject M, both while resting and while walking under controlled conditions, expended less energy than the other subjects and, as a result, exhibited less physiological strain.

The level of energy expenditure in performing standardized tasks may be a useful guide to the amount of strain that will be exhibited by a person in excessively hot conditions, and to the periods for which he can survive them. It is suggested that this may be of importance in the selection of people for work that involves the hazard of extremely hot conditions.

Physiological Measures of Thermal Stress

In these experiments, the increase from one speed of walking to the next was only 0·4 m.p.h.; however, each of these small increments in speed produced an increase in energy expenditure and therefore increased the total thermal stress to which the subjects were exposed. The various physiological responses were compared with respect to the accuracy with which they reflected such small increments of stress. In considering such comparisons, it must be remembered that the sweat loss values represent integrated measurements of the changes occurring over the whole reference period, whereas the measurements of heart rate and skin and rectal temperatures were obtained as single measurements at the stated times during the experimental period.

Sweat production exhibited a proportionately larger increase with increasing walking speed, and also reflected more closely the differences between the subjects in their levels of energy expenditure and in their changes in energy expenditure with increasing walking speeds, than did pulse rate, rectal temperature or mean skin temperature. It is therefore concluded that the measurements of sweat production provided the best indication of the degree of thermal stress imposed on each subject.

It should be noted, however, that when the results of the first two weeks and those of the second two weeks were compared, whereas no significant change in energy expenditure with time was found, the amount of sweat produced was shown to have changed. The effect was in opposite directions for the two pairs of subjects. P and M, especially M, had higher sweat losses, whereas B and W, especially B, had lower sweat losses in the second half of the series. These inconsistent changes in sweat production during a series of experiments lasting one month suggest that the sweat loss response of individuals exposed to constant conditions can alter from time to time without apparent cause.

The analysis of heat exchange summarized in Table 90 shows that the heat produced by metabolism was lost from the body chiefly by evaporative cooling. The convective heat losses were approximately twice as large as the radiation losses, but both were small because the mean skin temperatures were only a little above the air temperature (see Fig. 28). The changes in heat storage were also small. A period of low overall change in body temperature was purposely chosen for this analysis, since the calculation of the equivalent change in heat content of the body for large alterations in body temperature may introduce serious errors. It is worthy of note that drinking only 500 ml. of moderately cool water reduced the amount of heat that needed to be eliminated by about 34 B.Th.U., which is roughly equivalent to the total heat loss from the body by radiation during the 80-min period.

The effect of increasing the average speed of walking from 2·4 to 3·6 m.p.h. is interesting. The increase in metabolic heat production was accompanied by a proportionately greater increase in heat elimination by evaporation, and the convective and radiant heat losses both decreased.

If the behaviour of the two pairs of subjects is compared it can be seen that the difference in body surface area of these two pairs has influenced the response obtained. The B and W pair eliminated a larger proportion of their metabolic heat by evaporation and less by convection and radiation than the P and M pair. The differences between the two pairs of subjects and the effect of increasing their rate of energy expenditure on the relation between the working sweat loss and energy expenditure is illustrated in Fig. 30.

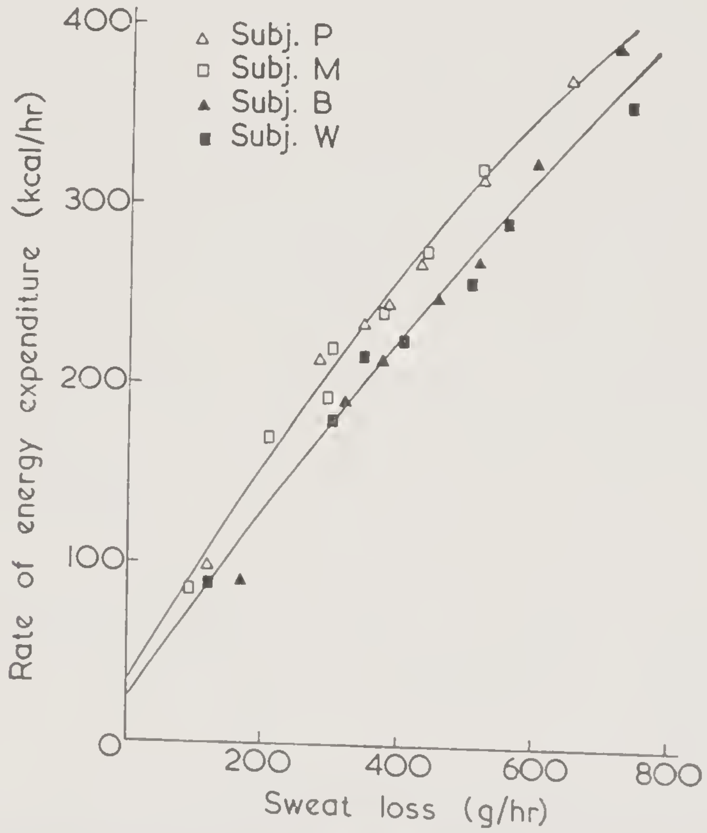

FIG. 30. Series VIIIa. The relation between the rate of energy expenditure and sweat loss for the two pairs of subjects.

Table 91 compares the predicted maximum evaporative heat loss for the two pairs of subjects at the two walking speeds, when the skin surface is completely wetted, with their estimated actual heat losses by evaporation of sweat in this climatic environment.

The comparison shows that the advantage enjoyed by the P and M pair was largely a result of their greater surface area. The most marked difference between the two pairs is evident at the higher walking speed and at this speed the actual evaporative heat losses by B and W were approaching the limiting value imposed by their maximum evaporative capacity.

Table 91 illustrates a problem which arises when attempts are made to define the maximum evaporative capacity. It will be noted that a smaller maximum evaporative capacity is predicted at the higher than at the lower walking speeds, because the skin temperatures were lower and this resulted in reduced vapour pressure differences between the air and the skin surface. Predicting the maximum evaporative capacity of the body using the observed skin temperature for a low heat stress ignores the alteration in skin temperature that may accompany the response to a higher thermal stress requiring a completely wetted body surface for the maintenance of thermal equilibrium. Furthermore, the maximum evaporative capacity can increase still more, after the state of a completely wetted body surface has been reached, if the skin temperature rises as the result of heat storage by the body. There is at present no means of predicting the skin temperature and, until this is possible, it would seem that the maximum evaporative capacity must be defined as the heat loss per hour by evaporation of sweat for the prevailing skin temperature and environmental conditions, when the naked body is completely wetted.

Under conditions of heat stress, the three most important regulatory mechanisms involved are vasomotor adjustments, sweating and heat storage. In general terms, as the heat stress increases these three mechanisms come into operation in the above order, playing the dominant role in heat regulation at low, medium and high thermal stresses respectively.

The relatively easily measured changes which occur when man enters a hot environment include those in the skin and deep body temperatures, in the body weight (through evaporative loss of fluid), in the heart rate and in sensations of relative comfort and discomfort. The measurement of weight loss provides a good measure of the activity of the sweating mechanism. Alterations in the skin and deep body temperatures can provide a measure of the changes in heat storage, but uncertainties as to the magnitude of temperature gradients throughout the body and technical difficulties in obtaining the measurements impair their value. None of the easily-obtained objective measurements of response provides a direct measure of the activity of the vasomotor mechanism, although alterations in heart rate and the difference between skin and deep body temperature may reflect changes in its level of activity under certain conditions. The subjective appreciation of warmth is a relatively sensitive indication of any alteration in the thermal stress of the environment and particularly in those environmental conditions in which the vasomotor mechanism is the most important heat-regulating mechanism.

It would appear, therefore, that the easily obtained objective measurements can only provide accurate information as to the activity of two out of the three main thermo-regulating mechanisms and that no single measurement of physiological effect can be expected to reflect accurately the stress of exposure to the full range of environmental heat loads.

It is of interest to consider whether an index based on the principles of partitional calorimetry could be devised to meet the requirements of both accuracy and simplicity. The key problem in producing such a formula is the necessity to predict or measure the skin temperature, since this is not only one of the most important physiological variables determining the magnitude of heat flow between the body and the environment, but it is also difficult to measure accurately. To solve this problem Haines and Hatch (1952) made the assumption '. . . that a worker who maintains thermal balance with the environment with an average skin temperature of 95°F does not find the accompanying stress of serious consequence. The assumption was made only to provide a bench mark from which to calculate the excess of the need for evaporative cooling to maintain thermal balance over the actual maximum evaporative capacity.' Similarly Plummer, Ionides and Siple (1945) assumed a safe skin temperature limit of 97 F when they proposed their Thermal Acceptance Ratio, an index which expresses the stress of exposure to hot conditions as the ratio of the maximum heat stress that can safely be tolerated to the actual strain imposed by heat and activity. Unfortunately, there is clearly no single value for a safe skin temperature limit which will suffice for all conditions.

It is possible that a sounder approach to this whole problem may be to begin by defining the maximum rise in deep body temperature that can be safely permitted, even though this also may need to be modified in some measure for the particular environmental conditions and level of activity of the individual exposed.

Having defined the permissible rise in deep body temperature, it would then be necessary to construct a nomogram, or table, capable of predicting the appropriate skin temperature for any combination of the environmental conditions and metabolic rate of an individual exposed, at the time of reaching thermal equilibrium with his surroundings or when his deep body temperature had risen to the safety limit. The ability to predict the skin temperature for any given set of conditions would enable accurate estimates to be made of the heat flow through the several avenues of evaporation, convection, radiation and (if required) conduction. The total heat gained by an individual of given size from all sources, including his metabolism, could then be expressed, in the way suggested by Haines and Hatch (1952), as a percentage of his total capacity to eliminate heat. For conditions in which the heat gain exceeded the eliminating capacity, the length of exposure, in minutes, before the rectal temperature would reach the accepted safety limit could also be predicted. A further and extensive series of experiments would be needed to produce a nomogram for predicting skin temperature, but there would seem to be no insuperable problems involved in such a project.

Series VIIIb: Sweat Losses in Different Patterns of Energy Expenditure

The second part of this series (Series VIIIb) was designed to test the validity of the assumption—apparently inherent in the P4SR nomogram—that the effect of the heat of metabolism on the sweat loss response of individuals exposed to hot climates is determined solely by the mean level of energy expenditure, and is not affected by fluctuations in the rate of energy expenditure during the reference period. This assumption implies that when exposed to the same climatic conditions and expending the same total energy in a given time, men working steadily and men engaged in alternating periods of work and rest will lose the same amount of sweat. To test this, the energy expenditure and the sweat losses were measured for three separate work routines, all extending over the same period of time and requiring the same total expenditure of energy but differing in their patterns of energy expenditure. In the first routine, the subjects alternated between resting seated for 15 min and walking on the treadmill for 15 min; in the second routine, the subjects walked slowly, without resting, throughout the reference period; in the third routine they alternated between walking for 30 min and resting for 30 min.

METHODS

The methods used followed very closely those of the first part of this series of experiments. The same environment (dry-bulb 90°F, wet-bulb 80°F, air speed 300 ft./min) and the same four subjects were used. The three experimental routines are shown in Fig. 31.

Eighteen working days were devoted to the experiment, the pairs of subjects being examined on alternate days. The effect of each of the three routines was

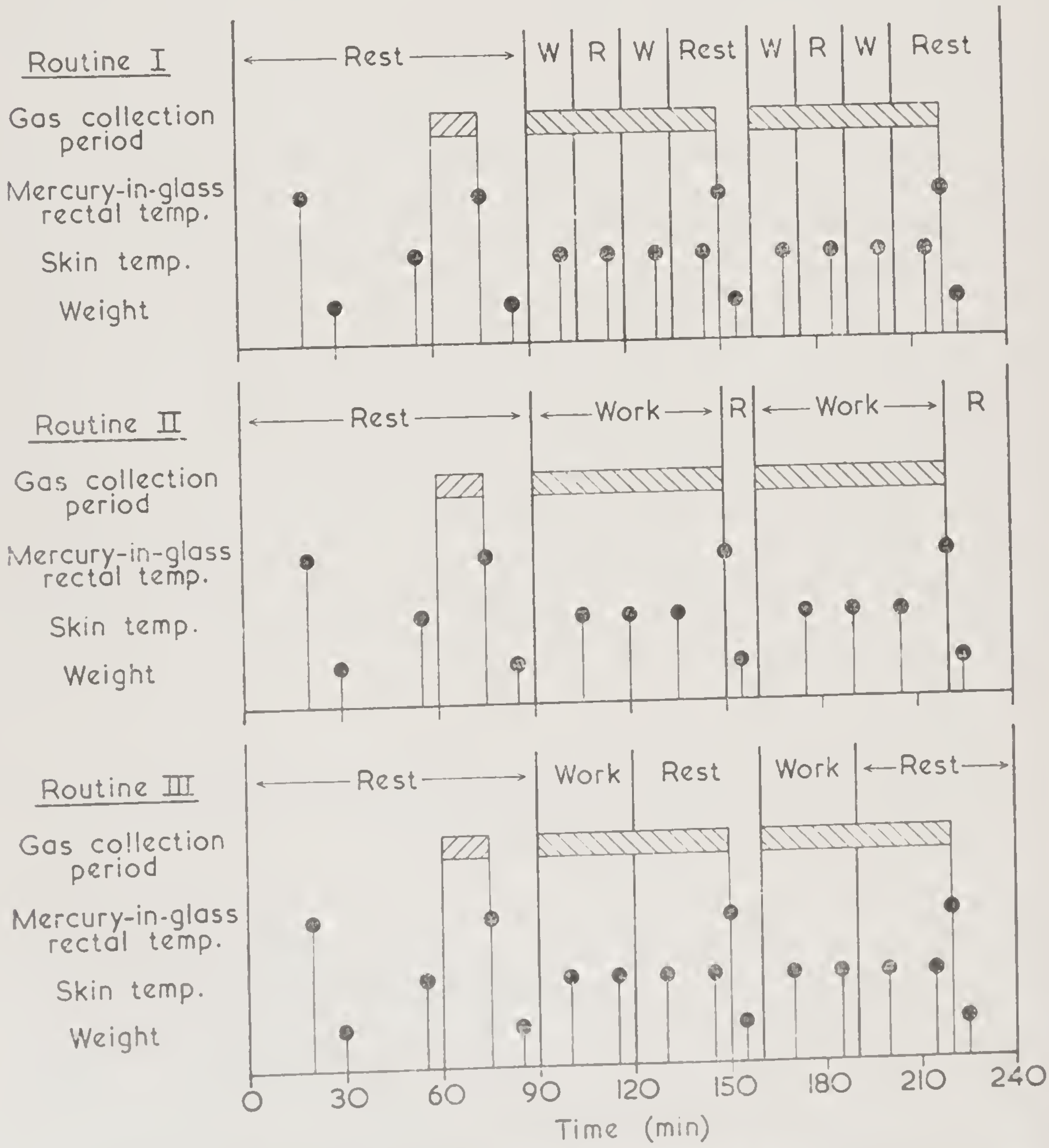

FIG. 31. Series VIIIb. The three experimental routines used in determining the effect of the pattern of energy expenditure on sweat loss.

examined three times for each pair, the routine to be used each day being chosen randomly. During each experimental session, as can be seen from Fig. 31, the effect of the routine was examined twice; the results of these two examinations are referred to as those of the first and second work periods.

The speeds at which each pair of subjects walked on the treadmill in each routine were as follows:

Subject pair	*Routine*	*Walking speed (m.p.h.)*
B & W	I	3·42
	II	2·00
	III	3·42
P & M	I	3·86
	II	2·00
	III	3·86

These values were chosen (on the basis of the results obtained in the previous experiments) in order to ensure that the total energy expenditure of both pairs of subjects would be the same in all three routines.

RESULTS

Energy Expenditure and Sweat Loss

Analyses of variance were performed on the net walking (working minus resting) energy expenditure and sweat loss values. A summary of the significant effects from these analyses is shown in Table 93.

These analyses showed that neither the energy expended nor the sweat loss response of the B and W pair differed significantly between the three routines. There were, however, significant differences in the energy expended on the three routines by the P and M pair and, probably as a result, the sweat losses also differed.

The analyses also provide some further information on the behaviour of the subjects during the experiments. The energy expended by B and W in the second work period was less than in the first work period, but their sweat losses were not similarly affected. This difference may have been caused by the greater variability of the sweat loss. For P and M there was no significant difference between the two work periods.

The two subjects comprising each pair differed significantly in their levels of energy expenditure and this was reflected in their sweat losses. These differences between the subjects were expected, since it had previously been shown that the energy expenditure of P, B and W was closely related to their respective body weights; but M, who was the largest of the four, nevertheless expended markedly less energy at the same walking speed.

The absence of any significant 'time' effects shows that the response of the subjects to the routines remained constant throughout the series of experiments.

The fact that the energy expended on the three routines differed significantly for the P and M pair probably explains, in part at least, the significant difference in net working sweat loss in the three routines. Since, as Fig. 30 clearly shows, the relation between sweat loss and energy expenditure was almost linear, the sweat losses were expressed per unit of energy expended (g/kcal) and these values were submitted to analyses of variance. The significant effects are shown in Table 94. There was no difference between the three routines in the amount of sweat lost per kcal of energy expended.

There were no significant differences between the two work periods for B and W, but for P and M the sweat loss per kcal expended was slightly higher in the second period than the first. This effect was entirely caused by P, as shown by the significant interaction between subject and period for this pair of subjects.

The sweat loss per kcal expended differed for the two subjects in each pair of subjects, B exhibiting the highest value and M the lowest.

Rectal Temperature

The mean rectal temperatures for each pair of subjects, measured twice before work and again after each work period, are shown in Fig. 32. The mean values for each pair before the first work period and after the second work period are compared in Table 95.

Skin Temperature

Mean values for each pair of subjects separately are shown graphically in Fig. 33. A comparison of the mean skin temperatures during the three experimental routines for the two pairs of subjects separately is shown in Table 96.

DISCUSSION

It has been shown that although the net energy expended on the three routines differed for one pair of subjects, thus excluding a direct comparison of the sweat losses, the amount of sweat lost for each kcal of energy expended in the three routines did not differ significantly for either pair of subjects. From this it is concluded that in terms of sweat production per kcal of energy expended no significant difference in physiological response could be detected between the three routines.

The problem can be further considered in terms of heat exchange, according to the equation

$$M \pm S = E \pm C \pm R \pm Cn.$$

A change in one term of this equation requires compensating changes in one or more of the remaining terms, in order to fulfil the requirements of thermal equilibrium. Thus, a difference in the relation between sweat production and energy expenditure in the three routines would have required either a difference in the amount of heat stored, or a change in the convection, radiation and conduction avenues of heat exchange. The former would be indicated by a rectal temperature difference, and the latter by a difference in the mean skin temperature level.

Mean rectal temperatures for the three routines agreed closely (Table 95). Mean skin temperatures for the three routines were also in good agreement except that the skin temperatures of subjects B and W appeared to be somewhat lower in Routine II than in I and III (Table 96). In general, the skin and rectal temperature measurements provide no evidence that the difference in pattern of work and rest affected the magnitude of heat lost through the various avenues of heat exchange.

It is possible, however, to specify certain special conditions in which the relation between sweat loss and energy expenditure would be expected to be

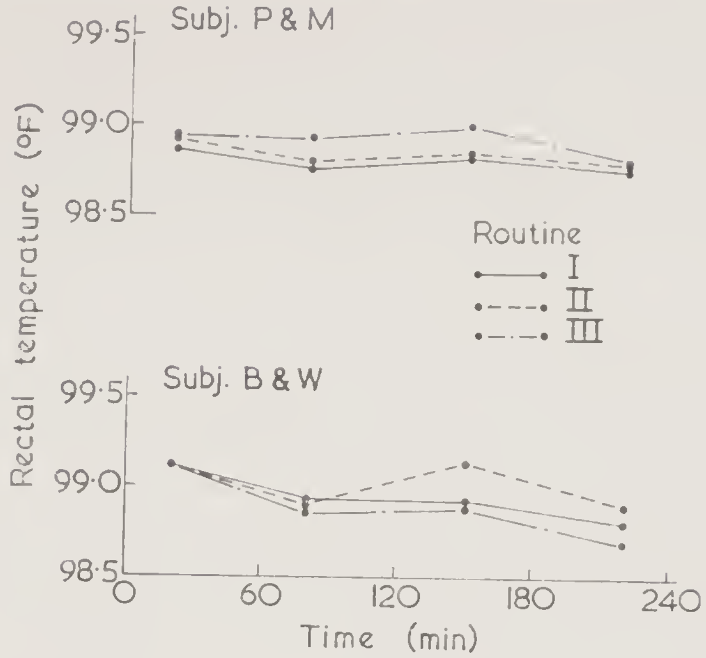

FIG. 32. Series VIIIb. Rectal temperature during each of the three work routines. The mean values for each pair of subjects are shown separately.

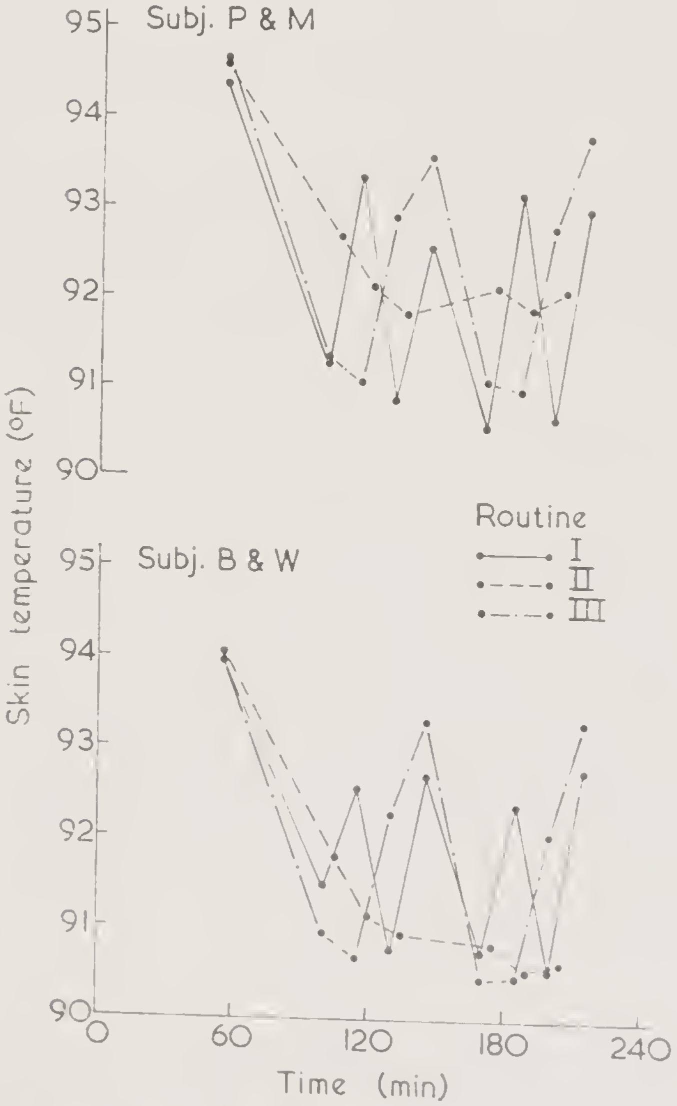

FIG. 33. Series VIIIb. Mean skin temperature during each of the three work routines. The mean values for each pair of subjects are shown separately.

influenced by the nature of the experimental routine. The following are three important examples:

(i) Routines in which a burst of activity occurs near the end of the reference period. Heat storage would be present at the time of the final weighing and, as a result, sweat losses would be lower than for routines with the same total energy requirements but in which the energy is expended steadily.

(ii) Routines requiring marked changes in the level of energy expenditure in hot wet climates. In hot wet climates, the increase in thermal stress caused by high rates of energy expenditure results in more sweat than can be evaporated from the body. The excess sweat drips from the body without cooling it and under these conditions the amount of sweat lost for each kcal of energy expended is considerably increased. A routine with alternating periods of high and low energy expenditure would be expected to cause therefore a greater sweat loss than a routine in which the same total energy had been expended steadily over the reference period.

(iii) Routines requiring marked changes in the level of energy expenditure in climates of low thermal stress. In a climate of low thermal stress and with a steady rate of energy expenditure, thermal equilibrium could be maintained by losing heat through convection and radiation. In the same climate and with the same total expenditure of energy, but in a routine of alternating periods of working and resting, sweating would occur during the work periods.

In summary, then, it may be said that although these experimental results showed that the distribution and pattern of work and rest throughout the experimental period had no special effect on the heat regulating mechanism, there are certain special circumstances in which the sweat production would be expected to be affected by the nature of the experimental routine.

Series VIIIc: The Energy Expenditure of Step-climbing

As the P4SR value for a given climate depends upon the rate of energy expenditure, the value for the P4SR Index for men performing the 'Queen Square Routine' will depend upon the value assigned to the energy cost of the routine. In London, Dunham *et al.* (1946) had obtained a value of 111 kcal.m^{-2}.hr^{-1} for this; in Singapore Adam *et al.* (1952) had obtained the value of 100 kcal.m^{-2}.hr^{-1}. It was therefore considered desirable to obtain further measurements, using another group of subjects, of the energy expended in the 'Queen Square Routine' at Singapore. The third part of Series VIII (Series VIIIc) was devoted to obtaining these measurements.

METHODS

The four subjects and the environmental conditions previously used in this series were also used on this occasion.

It was possible to measure the energy expenditure of only two subjects on any one day, and therefore each pair of subjects was investigated on alternate days, when four separate estimates were made for each member. On the intervening days they performed the 'Queen Square Routine' in another part of the climatic chamber but without measurement of their oxygen consumption. The experimental procedure and the times during the experimental routine at which pulse rates, rectal and skin temperatures, and body weights were measured are shown graphically in Fig. 34. The subjects wore white drill shorts and sandals. Each subject drank 500 ml. of water before the experiment began and a further 500 ml. just before the work period.

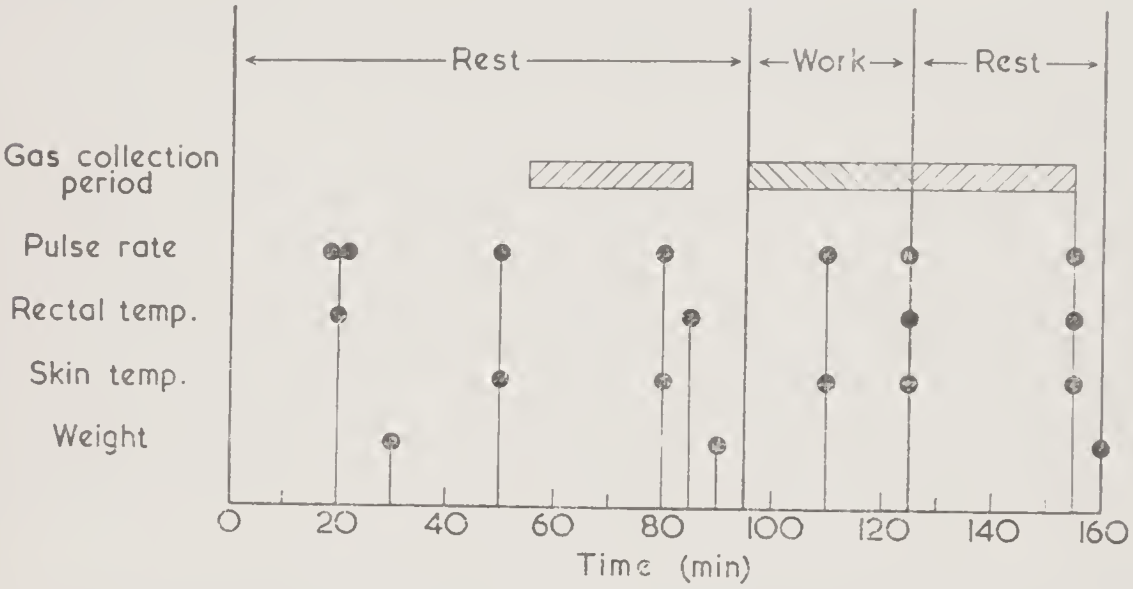

FIG. 34. Series VIIIc. Experimental routine used in determining the energy cost of step-climbing.

The experiments were arranged so that the effects of time and of the positions occupied by the subjects could be examined. (These effects were found to be negligible and so have not been separated from the estimate of error.)

RESULTS

In Table 97 are set out the mean values of the four measurements of the energy expended by each of the four subjects while step-climbing, corrected for the oxygen debt, and expressed as total energy expended, and as energy expended per unit body weight and per unit surface area. This table also gives the mean values of the four measurements of the subjects' energy expenditure while resting seated on stools, expressed per unit body surface area.

In Table 98 the estimates of the energy expenditure for resting and for step-climbing by Dunham *et al.* (1946), Adam *et al.* (1952) and Adam and Cague (1952) are compared with the estimate from the present series. The values quoted by Adam *et al.* (1952) and by Adam and Cague (1952) are different estimates from the same series of experiments.

Table 99 compares the physical characteristics of the subjects in the present series with those of Adam and Cague (1952) and Dunham *et al.* (1946).

DISCUSSION

The variability of the measurements reported by Dunham *et al.* (1946) is not known, but when their results are compared with those of the present series it is clear that there was no significant difference in the energy expended by resting subjects in London and in Singapore, whereas, unless the variability of the former measurements was very high, the energy expended on step-climbing was lower in Singapore than in London. If the values quoted by Adam and Cague (1952) are compared with those of the present series (Table 98) it can be seen that the energy expended on step-climbing did not differ significantly, but that the energy expended on resting was lower in the former series than in the latter. These findings can be summarized by saying that the measurements of energy expenditure on step-climbing in the two Singapore series are in agreement, but lower than the results reported in London, whereas for resting energy expenditure the results from the present series are in agreement with those obtained in London and both are apparently higher than those reported in the earlier series at Singapore.

It is thought that these apparently conflicting findings can be explained by the fact that there was one important difference between the techniques adopted in the present, and in the two previous, series. In the two earlier series (in London and in Singapore), the subjects—when resting—sat in canvas-backed chairs which were conducive to good muscular relaxation, whereas in the present series subjects sat on wooden stools without back supports. (This change in the routine from resting in chairs to resting on wooden stools was made after the third series of experiments (Series III) and adopted in all series thereafter.) It seems likely that the observed slight increase in resting energy expenditure in the present series over that of the earlier Singapore series reflected this change in posture.

The results of the two Singapore series would appear therefore to be in good agreement, and the comparison with the London results strongly suggests that when performing the same amount of work the Singapore subjects expended less energy than those in London.

Summary

1. An account is given of the eighth series of experiments (Series VIII) performed at Singapore.

2. In the first part of the series, four subjects walked on a treadmill at six speeds (2·0, 2·4, 2·8, 3·2, 3·6 and 4·0 m.p.h.) at dry-bulb temperature 90 F, wet-bulb temperature 80 F and an air speed of 300 ft./min. Sweat losses, pulse rates, and skin and deep-body temperature were determined at intervals and the energy expended by the subjects while both resting and working was measured by indirect calorimetry.

3. The resting sweat loss of each subject was proportional to the energy expended while at rest. For each increment of 0·4 m.p.h. in the speed of walking there was (with a single exception) a significant increase in the energy expended. Similarly, for each increment in speed there was (with one exception) a significant increase in the amount of sweat produced. The amount of sweat produced per kcal expended differed somewhat from subject to subject but was not affected by the rate of energy expenditure. The energy expended per mile per kilogram body weight increased slightly from 2·0 to 3·6 m.p.h. and markedly between 3·6 and 4·0 m.p.h.

4. Pulse rate, skin temperature and rectal temperature did not show the consistently close relation to the rate of walking shown by the sweat loss. It

was concluded, therefore, that the sweat loss provided the most accurate indication of the changes in thermal load produced by alterations in the rate of working and reflected most accurately the differences between individuals in their pattern of energy expenditure.

5. One subject consistently expended less energy and secreted less sweat than the remaining three, and, as he was the largest subject, expressing the results in relation to body size did not remove this difference.

6. The sweat losses in the one-hour reference period consistently exceeded one fourth of the P4SR value for the experimental conditions.

7. A detailed analysis of the thermal exchanges of the subjects showed good agreement between the metabolic heat production and the estimated heat loss to the environment.

8. The rates of energy expenditure of the subjects were within the range observed for similar tasks in temperate climates.

9. The differences observed in the amount of energy expended by each subject indicate that, in climatic physiology experiments, it cannot be assumed that if all the subjects perform the same standard task under carefully controlled conditions the energy expenditure will be the same for all. It seems essential that the characteristic energy expenditure level of each subject should be determined.

10. It is possible that the characteristic rate of energy expenditure may be of importance in the selection of personnel for special types of work involving the hazard of extremely hot conditions.

11. The possibilities of devising an index of the physiological effects of hot environments based on the principles of partitional calorimetry are discussed. The advantages are outlined and it is pointed out that for such an index it would be necessary to devise a means whereby the skin temperature could be calculated for any set of environmental conditions.

12. In the second part of the series it was shown, by comparing the effects of three different patterns of working and resting having the same total energy expenditure, that, over the range examined, the pattern of energy expenditure did not affect the total amount of sweat lost or the magnitude of the heat losses through the various avenues of heat exchange. Attention is drawn to those conditions for which this conclusion would not be expected to hold.

13. The third part of the series was devoted to determining the energy expenditure of the component parts of the 'Queen Square Routine'. It was found that the mean value for sitting at rest was 54·80 (S.D. 2·88) $\text{kcal.m}^{-2}.\text{hr}^{-1}$ and for step-climbing, 166·90 (S.D. 5·16) $\text{kcal.m}^{-2}.\text{hr}^{-1}$.

CHAPTER 8. THE UPPER LIMITS OF TOLERANCE OF ENVIRONMENTAL STRESS

An account of the work of F. P. Ellis, Helen M. Ferres, A. R. Lind and P. S. B. Newling

As the time available at Singapore drew to a close, a survey of the work done showed that the proposed body of research had largely been completed. The information that had been gathered on the upper limits of tolerance for hot environments was, however, considered to be inadequate. It was true that observations had been made on this subject in the course of the experiments already completed but these observations could only be regarded as accidental. It had become increasingly obvious, with time, that cases of heat illness seriously detracted from the value of experiments in which they occurred, so that precautions were taken to avoid them wherever possible. The result was that no systematic knowledge had been acquired of the upper limits of tolerance for heat 'of men who are exposed daily to high temperatures in the fleet'.

There was in addition a further matter the importance of which, though unsuspected in the earlier series of experiments, became increasingly apparent as the work progressed. This was the effect of water intake on the amount of sweat secreted. Examination of the results of the uniformity trials of Series III (Adam, Ellis, John, Lee & Macpherson, 1953), which will be referred to more fully in Chapter 10, appeared to indicate that increasing amounts of water drunk resulted in increasing amounts of sweat secreted. The findings in Series IV, referred to on p.p. 87-9, appeared to confirm these suspicions. It was therefore considered important that the matter should be settled beyond reasonable doubt.

The last series of physiological experiments which was performed at the Tropical Research Unit (Series IX) was undertaken to provide information on these two topics, and the results have been set out in full in three reports: 'The effect of water intake on men working in warm atmospheres in the tropics' (Ellis, Ferres & Lind, 1953); 'The upper tolerable levels of warmth for acclimatized European men working in the tropics' (Ellis, Ferres, Lind & Newling, 1953); and 'Observations on the incapacitation of men at rest in warm humid atmospheres' (Ellis, Lind & Newling, 1953).

Series IX: The Effect of Water Intake in the Heat

Robinson (1949) summarized the then current views of hot-climate physiologists when he said 'Moderate water deficiency does not significantly alter the sweat rate and neither does drinking water in excess of the sweat loss'. Later, Ladell (1951) said 'In 110-minute exposures to the test climate there was no statistically significant variation in the sweat output of fully acclimatized subjects with changes in salt and water intake.' Experiments at Singapore, however, as mentioned above, led to the suspicion that sweat output might be related to the water intake more closely than was usually held to be the case. Furthermore, it was thought that, if this were so, the pulse rate and body temperature might likewise be affected by the water intake.

The changes in sweat loss, body temperature and pulse rate were therefore measured, under otherwise identical conditions, in relation to three levels of water intake. This was done during a twelve-day period when twelve young men were being acclimatized as a preliminary to taking part in the investigation of the upper limits of heat tolerance to be described in the second part of this chapter. The acclimatization period was preceded and followed by uniformity trials, and before the subjects were exposed to the high temperature of the acclimatization period they underwent a 6-day period of training in their subsequent work at a temperature representative of the usual climate at Singapore.

The reason for introducing this preliminary period of training was that one difficulty in understanding the exact meaning of the changes which occur during acclimatization experiments is in deciding to what extent these changes are due to the improved tolerance of muscular exercise resulting from repetition of the work that is done in them; indeed it was thought that such a 'practice' effect might obscure the effects due to variations in the amount of water drunk.

METHODS

Experimental Design

The 12-day experiment consisted of sixteen 3 × 3 Latin squares. The variables for each square were days, subjects and treatments (water intake). The sixteen Latin squares were arranged in four groups of four, one group for each 3-day period. The experiments lasted 2 hr for the first, 3 hr for the second and 4 hr for the third and fourth 3-day periods. The four squares in each group corresponded to four teams of subjects.

It was intended in this experiment that the men should be kept reasonably hydrated and, at the same time, that the effects should be examined of quite small variations in fluid intake. The three levels of water intake selected, which were based on information obtained in earlier experiments in which the subjects were allowed to drink as much fluid as they wished, were 550, 700 and 850 ml./hr.

The plan is illustrated below.

	Duration:	2 hours			3 hours			4 hours			4 hours		
	Day:	8	9	10	11	12	13	14	15	16	17	18	19
Team	*Subj.*												
I	1	B	C	A	C	A	B	A	C	B	C	A	B
	2	C	A	B	A	B	C	C	B	A	A	B	C
	3	A	B	C	B	C	A	B	A	C	B	C	A
II	4	C	B	A	B	A	C	A	B	C	C	B	A
	5	B	A	C	C	B	A	C	A	B	B	A	C
	6	A	C	B	A	C	B	B	C	A	A	C	B
III	7	A	B	C	B	C	A	C	B	A	B	C	A
	8	C	A	B	A	B	C	B	A	C	C	A	B
	9	B	C	A	C	A	B	A	C	B	A	B	C
IV	10	B	C	A	C	B	A	B	A	C	A	C	B
	11	C	A	B	B	A	C	A	C	B	C	B	A
	12	A	B	C	A	C	B	C	B	A	B	A	C

Water intake (ml./hr): A, 550; B, 700; C, 850

Subjects

The subjects were twelve soldiers, aged from 19 to 33 (mean 22) years, who had been in the tropics from 6 to 24 (mean 15) months. They were all medically fit.

Experimental Procedure

The environmental conditions for the water-intake experiment were dry-bulb temperature 100° F, wet-bulb temperature 94° F and an average air speed of 140 ft./min. The subjects worked naked, in bare feet. The working routine was designed to provide the same amount of work (step-climbing) in each hourly period. In summary it was as follows.

Time (min)	*Activity*
— 30– 0	Rest outside hot room
0– 10	Enter hot room and rest seated
10– 20	First work period
20– 40	Rest
40– 50	Second work period
50– 70	Rest
70– 80	Third work period
80–100	Rest
100–110	Fourth work period
110–120	Rest (Experiment ends, Days 8–10)
120–130	Rest
130–140	Fifth work period
140–160	Rest
160–170	Sixth work period
170–180	Rest (Experiment ends, Days 11–13)
180–190	Rest
190–200	Seventh work period
200–220	Rest
220–230	Eighth work period
230–240	Rest (Experiment ends, Days 14–19)

During the 12 days, one senior technician was responsible for the water supply. Water was supplied at half-hourly intervals in a glass tankard painted red, white or blue. Each subject had a red, white or blue letter, A, B, or C, tied round his right wrist to enable the technician and the subject to check that he was receiving the correct drink. Each tankard had a black line drawn on it to show the level to which it should be filled with water, as an additional check.

The subjects were weighed before and after, and at hourly intervals during each experiment and their fluid intake and output during the experiment were measured. (The sweat loss was assumed to be the difference between the sum of the weight loss and the amount of fluid drunk and the fluid output. The fluid losses in expired air were ignored. The sweat loss was expressed as the loss per kilogram of the body weight at the beginning of the experiment.)

The pulse rate and rectal temperature were recorded before and after each work period. Before work the pulse was recorded in the sitting position. The subject then stood up and, after a minute, the pulse was recorded in the standing position. After he stopped work the pulse (standing) was counted immediately.

The subjects were given one gram of salt (as sugar-and-enteric-coated half-gram tablets) for each kilogram of weight lost as sweat during an experiment. The first specimen of urine passed by each subject after reaching the Unit each morning was tested for chlorides (Fantus, 1936).

The preliminary training period lasted 6 days. On the first 2 days the subjects followed the step-climbing routine of the succeeding experiment for 2 hr, on the third and fourth days for 3 hr, and on the fifth and sixth days for 4 hr. This was done at dry-bulb temperature 85°F, wet-bulb temperature 75°F. The subjects wore drill shorts. During this period, when very little sweating occurred, they were given 250 ml. of water per hour.

The uniformity trials which preceded and followed the main experiment lasted for 2 hr and the routine followed that for the first 2 hr in the experiment. During the uniformity trials each subject was given 700 ml. of water per hour. The environmental conditions were those of the water-intake experiment, dry-bulb temperature 100 F, wet-bulb temperature 94 F, and an average air speed of 140 ft./min. The subjects again worked naked, in bare feet.

RESULTS

The Effect of Training

Examination of the results showed that during the 6-day training period there was no change in the amount of sweat lost in the first 2 hr. Similarly, there was no change in the heart rate at the end of the fourth work period. There was, however, a fall of 0·5 F in the mean rectal temperature at the end of the fourth work period and this result was statistically significant.

The Effect of Acclimatization

As the average intake of water for the twelve subjects was 700 ml./hr on each day of the acclimatization period, the design of the experiment made it possible to separate the effect of time, i.e., acclimatization, from the effect of the treatment, i.e., the amount of water drunk.

Sweat loss. The mean sweat loss for the twelve subjects during the first 2 hr of the 12 days of the acclimatization period (expressed per kilogram of body weight) is set out in Table 100. In contrast to the absence of change in sweat loss during the training period there was an increase in the amount of sweat lost, but the rate of increase diminished somewhat towards the end of the period.

Rectal temperature. The mean rectal temperature of the twelve subjects at the end of the fourth work period is also given in Table 100. There was little change during the first 6 days but there was then a slow decrease, so that the value on the twelfth day was about 0·3°F lower than on the first day. These results, taken in conjunction with those of the training period, would indicate that the fall in body temperature which occurs when men are repeatedly exercised in a hot environment is an effect of acclimatization to heat as well as one of habituation to muscular exercise.

Pulse rate. The standing pulse rates, recorded at the same time as the rectal temperatures, are also set out in Table 100. As with the rectal temperature, there was little change during the first half of the acclimatization period, and then a small decrease. This appears to be an acclimatization effect, as there was no corresponding fall in the training period.

The Effect of Water Intake

Sweat loss. When the sweat losses during the first 2 hr of exposure to heat on the 12 days of the acclimatization period were examined, no significant difference was found in the effects of 'treatment'. There was, however, a significant difference after 3 hr in the last 9 days of the period. The effect of the treatment, however, is more easily seen when the sweat losses for the 4 hr exposure on the last 6 days are examined. These are set out in Table 101. Those receiving the least amount of water produced the least amount of sweat, and those receiving the greatest amount of water the greatest amount of sweat. This effect became more marked with the passage of time. During the first hour there was no difference. During the second hour a difference became apparent and this became more marked during the third and fourth hours. It is worth noting that in all cases the amount of sweat secreted reached a maximum during the second hour and then declined.

Rectal temperature. Analysis of the rectal temperature at the end of the third work period throughout the acclimatization period showed that those who received the least amount of water had a significantly higher rectal temperature than the other two groups (Table 102).

Analysis of the rectal temperature after the first, third, fifth and seventh work period during the last 6 days of the acclimatization period (Table 103) showed that the effect of treatment became most apparent during the fourth hour. At the end of the seventh work period, those receiving the smallest amount of water had the highest rectal temperature and those receiving the largest amount the lowest rectal temperature.

The effect is further illustrated in the table of mean values for the rectal temperature after the second, fourth, sixth and eighth work periods (Table 104).

Pulse rate. The effect of variation in the water intake on the heart rate was less marked than its effect on sweat loss or on rectal temperature. Nevertheless, a small effect could be demonstrated. Table 105 sets out the mean pulse rates after the first, third, fifth and seventh work periods during the last 6 days of acclimatization. Those receiving the least amount of water had a significantly higher pulse rate than those receiving the most. This effect, though it is small, can also be seen in the mean values for the pulse rate after the second, fourth, sixth and eighth work periods (Table 106).

The Effect of Repeated Exposure to Hot Conditions

The mean values for the sitting and standing pulse rates, rectal temperatures, and sweat losses of eleven subjects at the end of the two-hour uniformity trials held before and after the period of acclimatization, and of others held during the subsequent period of exposure to extreme conditions (in the experiment to be described next) are shown in Table 107. The most important adjustment appears to be an average initial increase during the acclimatization period (Days 8–20) of about 60 per cent in the amount of water lost. After this an apparent equilibrium was reached. The other changes were small.

The subjects' awareness of their water requirements changed after they had had repeated experience of high temperatures. After the first section of the acclimatization series, and after the second uniformity trial (at the end of this series), they completed a questionnaire to indicate which of the three amounts of water used during acclimatization suited them best. Ten out of the twelve preferred the intermediate amount—700 ml.—when first questioned, but all of them preferred 850 ml. when they were questioned the second time. When first questioned one man found 550 ml. adequate but he later changed his mind.

DISCUSSION

The fall in the mean body temperature of the group during the training period was greater than the subsequent fall with work in a hot moist atmosphere. It appears likely that this 'acclimatization effect' is due to repeated work at least as much as it is due to repeated exposure to a warm climate. The changes in the levels of pulse rate and sweat output which were evident during the acclimatization period were not apparent during the training period, so it is probable that these are due to the effects of the warm climate rather than to the combined effects of the warm climate and training.

Under the conditions of this experiment the view of Robinson (1949) that 'moderate water deficiency does not significantly alter the sweat rate' requires qualification. The subjects did not take in quite as much water by drinking as they lost by sweating, but even on the smallest ration of water they were not experiencing severe water deficiency; nevertheless their sweat output did vary with the water intake. The experiment provides no evidence concerning the second part of Robinson's statement—'neither does drinking water in excess of sweat loss [significantly alter the sweat rate]'—but this is of less practical importance. Men rarely replace their sweat losses by drinking voluntarily when they are working at high temperatures for 3 or 4 hr, and very rarely rehydrate to excess, although they usually restore their body fluids within 24 hr if they do not in the meantime again engage in work at high temperatures.

The results are consistent with the observation of Ladell (1951) that there was no statistically significant variation in the sweat output of fully acclimatized subjects with changes in salt and water intake in experiments lasting less than 2 hr. The sweat losses during the first 2 hr of exposure to heat on all 12 days revealed no significant difference in the effects of treatment.

The results of the uniformity trials held during the 6-week period which followed the 'water intake' experiment (see Table 107) did not reveal the tendency shown by the subjects of Adam *et al.* (1952) to lose weight and sweat less with repeated work at high temperatures but, as Adam *et al.* were describing the results of 4-hr and not 2-hr uniformity trials, a direct comparison cannot be made. It can be stated, however, that the subjects of the series under discussion did not, as a group, show any evidence of becoming dehydrated, and that the daily Fantus' tests indicated that their urinary chloride losses were usually within normal limits despite the rigorous conditions they endured on the days between the uniformity trials. The procedure of adjusting the supplementary salt intake on the basis of the observed sweat output appeared to work satisfactorily in this case where the aim was not to replace the salt loss entirely by the extra ration, but under more rigorous conditions, or with prolonged or repeated exposure, a larger ration might well be necessary. None of the subjects experienced difficulty in swallowing the large numbers of sugar-and-enteric-coated salt tablets which were necessary, nor were unpleasant gastro-intestinal disturbances observed as a result of this, provided they did not swallow too many tablets at once.

These results indicate that in hot industries, or during military operations in warm climates, supplies of cool drinking water should be available in amounts which are at least equal to the sweat output under the prevailing conditions, and that free drinking should be encouraged. Men should not, however, be forced to drink more than they feel they require as this may do more harm than good.

The temperature of the water is important. Cool water is not only more palatable than tepid water, and therefore can usually be drunk in larger quantities, but it also helps to control the body temperature. No ill effects from drinking cool water were observed during several thousand experiments at Singapore.

Series IX: Upper Tolerable Levels of Warmth

At the conclusion of the period of acclimatization, the main purpose of this series of experiments was proceeded with. The aim of the experiments of this second part may be formally defined as the determination of the upper limits of tolerance for hot environments of healthy young men fully acclimatized to the effects of heat.

METHODS

Subjects

One of the twelve subjects used in the preceding experiments on the effects of water intake had to return to his unit for reasons unconnected with the experiments. The remaining eleven men acted as the subjects for these experiments.

Procedure

The men were exposed to test conditions for 4 hr on alternate mornings for 3 days each week, and on the intervening mornings they underwent the 2-hr uniformity trials previously mentioned (p. 162). They rested on Sundays.

The climates to be used were selected as the experiments continued. If one set of conditions proved excessively severe a rather milder climate was used next time. The details of the experimental climates are given in the next section with the results of the experiments. Except in one experiment, the average air flow, which was turbulent, was maintained constant at approximately 150 ft./min. This was chosen as representative of the air flow conditions likely to be encountered between decks in ships in the tropics.

The standard 'Queen Square Routine' (p. 15) was used. During the uniformity trials no clothing was worn. At other times, except where it is otherwise stated, the subjects wore naval drill overalls over shorts and canvas-and-rubber shoes. They were allowed to drink all the water they wished; it was supplied at 57 ± 3°F. Those subjects who found it too cool waited a few minutes for it to become warmer. As in the experiments on the effect of water intake, each man was given two enteric-coated salt tablets (each 0·5 g of NaCl) for each kilogram of sweat lost by him during the experiment. The urinary chlorides were estimated each day in the first specimen of urine passed by the subject after arrival at the laboratory. Weight loss, heart rate and rectal temperature were measured as in previous experiments. When subjects were incapacitated measurements of the blood pressure were made if an observer was available.

Criteria of Incapacitation

Each observer was responsible for only three subjects. He was instructed to inform the senior medical observer if any subject exhibited any of the following—

1. A pulse rate of over 80 beats/30 sec after work;
2. A pulse rate of over 70 beats/30 sec before work;
3. A rectal temperature of 102·5°F or higher;
4. A rise in pulse rate during rest period;
5. Definite signs of physical inability to cope with the task;
6. Evident cyanosis or circumoral pallor;
7. Complaints of unpleasant symptoms, e.g., faintness or cramp, etc.

RESULTS

The Upper Tolerable Limits

The dry-bulb and wet-bulb temperatures selected for the first series of eleven experiments are given in Table 108. The 'survival' rate for these environments is given in Fig. 35. Conditions under which no subjects were incapacitated, one to three were incapacitated and five or more were incapacitated are joined by separate lines. Also shown on the diagram is a line indicating a P4SR value of 4·5—in environments with values above this, McArdle and his colleagues

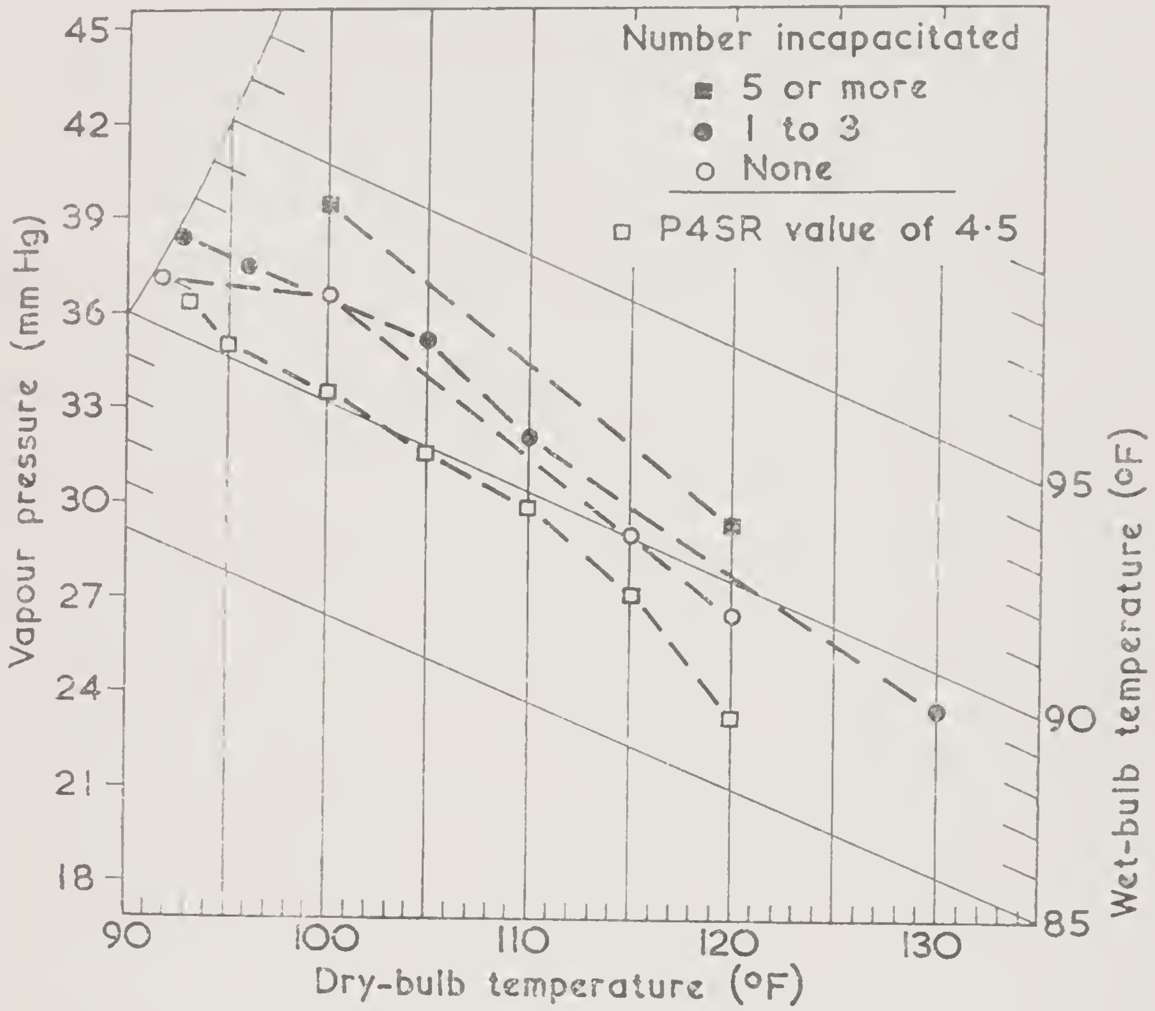

FIG. 35. Series IX. Number (out of eleven) of highly-acclimatized young men working in overalls in Singapore who were incapacitated by different climates (mean air speed 150 ft./min) and the corresponding limiting conditions (P4SR Index 4·5) estimated for 'fit acclimatized young men' in London.

predicted that an increasing number of fit acclimatized young men in London would be incapacitated. The position of this line indicates that the wet-bulb temperature above which the London men would be expected to be incapacitated is only 1–2 F below that at which casualties occurred in Singapore. This suggests that there is little difference between the upper tolerable levels of warmth for young men trained to work at high temperatures, whether they work in the tropics or in a temperate climate.

The results indicate that, as observed by Haldane (1905) and by many workers since, the wet-bulb temperature is a much more critical factor than the dry-bulb temperature in deciding whether a group will survive or be incapacitated. When the air temperature was 100°F or less, the wet-bulb temperature above which some men were incapacitated was 92 F. Above 100°F, the limiting wet-bulb temperature was lowered by approximately 1°F for each 10°F increase in air temperature up to 130°F. Very small increments in the wet-bulb temperature had a profound effect at this level of warmth. All the subjects completed their task with ease when the dry-bulb and wet-bulb temperatures were 120/89 F and 100/92 F, but the majority of them were incapacitated when the wet-bulb temperatures were increased only 2 F to 120/91 F and 100/94 F under conditions which were identical in other ways.

All the subjects completed the second work period in all the experiments. Those who subsequently became incapacitated did not usually outlast the third period of work. In Table 108 are shown for each experiment the mean rectal temperatures and standing pulse rates of all the subjects after the second period of work, and the mean four-hour sweat losses of the survivors. The indication of the relative severity of the climates that is given by the incidence of incapacitation (e.g., in Expt 4 and 5, and Expt 9 and 10) is supported by the mean body temperatures and pulse rates. For example, in Expt 5 and 10, in which the conditions proved to be intolerable for the majority of the subjects, the mean rectal temperature of the group after the second period of work exceeded 102°F; in the four experiments in which there were no casualties, the mean rectal temperature was 101·5 F or less. However, in the nearly saturated atmosphere of Expt 2—in which two men were eventually incapacitated—the mean rectal temperature of the group after the second period of work was only 100·9 F (and the pulse rate was only 71 beats/30 sec).

The mean four-hour sweat losses of the survivors, which ranged between 4 and 6 litres, did not in themselves provide an indication of the casualty incidence for the group. In Expt 3, in which two men were incapacitated, the mean sweat loss of the survivors was over half a litre less than in Expt 9 which all survived, although the respective levels of the mean rectal temperatures indicated the relative severity of the conditions correctly. These experiments showed that the ultimate tolerability of a warm environment cannot be predicted reliably from a consideration of measurements of body temperature, pulse rate or sweat loss under conditions which are not sufficiently severe to cause collapse, but should be determined wherever possible from the actual incidence of incapacitation amongst men working under the conditions in question. As was found in the earlier series at Singapore, there were considerable variations between individuals in their ability to tolerate very similar working conditions.

The Effects of 'Still' Air

Only one experiment was carried out in 'still' air (average speed, 20 ft./min). The effects were so dramatic that it was unnecessary to repeat it. The dry- and wet-bulb temperatures selected were 120 F and 89°F, a combination which all the subjects had endured already with comparative ease in a previous experiment when the air speed was 150 ft./min. Apart from this difference in air speed, the working conditions of the two experiments were identical. The 'still-air' experiment was discontinued shortly after the third working period, by which time six men were incapacitated and another was on the verge of collapse. This violent contrast in the extent to which the two sets of environmental conditions could be endured is given additional emphasis by the fact that the mean wet-bulb temperature for the 'still-air' experiment was 0·7 F below the target temperature (which had been maintained during the previous experiment) because the poor air circulation impaired the humidity control at one stage.

Measurements of pulse rate and body temperature were of little help in indicating the relative severity of these conditions (Table 109). Convincing evidence was provided only by the actual incidence of collapse.

The importance of ensuring brisk air movement between-decks in warships when men work at these levels of warmth is emphasized by these results. Changes in air speed which are barely perceptible may turn a tolerable climate into one which is intolerable if men work in these conditions for more than an hour or so.

The Effects of Radiant Heat and Clothing

Four experiments, each comprising two sessions with three subjects in the radiant-heat tunnel, were conducted in climates simulating fairly severe engine- or boiler-room conditions in the tropics. One of the six subjects, however, developed miliaria profunda during the course of the experiments and was excluded from further participation, so that information concerning only five subjects was obtained. In the first two experiments the subjects worked in naval overalls over naval drill shorts. In the first experiment the mean radiant temperature of the surroundings was 4°F less than the air temperature. In the second and third it was 17°F greater than the air temperature. In the third experiment the men discarded their overalls and worked in shorts only. In the last experiment they again worked in shorts, but the mean radiant temperature was increased by another 18°F.

The details of the climates, the average rectal temperatures and standing pulse rates of the five men after the most strenuous phase of each experiment, and the average sweat loss during each experiment, expressed as the loss per kilogram of the initial body weight, are shown in Table 110.

The five subjects all completed each experiment. They did their work efficiently and in good time. They were under the greatest strain and nearest to collapse in the second experiment when wearing overalls and with a moderate radiant-heat load. Although their mean sweat losses were similar when they worked stripped to the waist in the fourth experiment with the heaviest radiant-heat load, the lower average rectal temperatures after work supported the combined opinions of the subjects and observers that this was a less strenuous climate than the second, and was no more severe than the first. It would seem that the addition made by radiant heat to thermal stress under excessively warm conditions is not very great. Apart from the differences in the amount sweated, the effect of increasing the mean radiant temperature of the surroundings by 39°F was similar to the effect of working in overalls worn over shorts instead of in shorts alone.

In peacetime, the reasons for wearing overalls in machinery spaces in ships are that they protect against burns from unlagged hot parts or from steam leaks, keep the skin clean and protect against 'wild heat' (radiant heat). In war they also provide excellent protection against flash burns. The present observations suggest that, with the levels of radiant heat which are likely to be encountered in warships' machinery spaces, although overalls may protect against radiant heat this protection is more than offset by the added stress imposed by interference with ventilation of the body surface and evaporative cooling, and the additional weight and hindrance from wearing a sweat-soaked garment. It is unlikely, because of the above considerations, that the practice of working in overalls in machinery spaces will be changed. Consideration might, however, be given to the provision of overalls made of lightweight and more ventile fabrics for those who have to work in the machinery spaces of warships in the tropics in peacetime.

The Effects of Repeated Exposure

Two experiments were carried out to determine whether repeated and frequent exposure to climates near to the tolerance limit for working men would turn a tolerable condition into one which could not be tolerated. Under operational conditions men working in hot spaces are on duty for alternate four-hour watches when they are 'in two watches' and therefore the effects of two four-hour watches with an intervening rest of 4 hr were examined. Subsequently, the effects of three four-hour watches with intervening rest periods of 4 hr were investigated.

Nine men took part in the first experiment. The climate selected (dry-bulb temperature 110 F, wet-bulb temperature 88°F) was one which had been used in London (Dunham *et al.*, 1946) for observations on four men; it was chosen so that additional evidence might be obtained concerning the relative physiological responses of artificially acclimatized men in London and Singapore. Between the two four-hour exposures the men were kept under observation but were allowed to move about as they wished in the cooler climate of the laboratory (dry-bulb temperature 85 F, wet-bulb temperature 79 F).

The average sweat losses of the subjects during the experiment, and their average rectal temperatures and pulse rates, are shown in Table 111. The effects of the two exposures were similar except for the effect on rectal temperature. In view of the similarity between the pulse rates and between the sweat losses, and the similarity of the changes in rectal temperature with alternating work and rest periods in both exposures, it was considered likely that the higher evening rectal temperature was a normal diurnal variation. This was the mildest climate investigated during this series.

When the results were compared with those of the London experiments in a similar climate, no differences were found between the sweat losses, the rectal temperatures or the pulse rates for the four London subjects and the nine Singapore subjects but, with the few values available from London, this is inconclusive.

The climate selected for the second experiment was dry-bulb temperature 115 F, wet-bulb temperature 87°F, air speed 150 ft./min, and mean radiant temperature of the surroundings 132°F. It was the climate which had nearly caused the collapse of the five men wearing overalls in the radiant heat experiment, except that the wet-bulb temperature was lowered by 3°F. Three subjects wearing overalls carried out the working routine during each of three four-hour exposures. Between exposures they rested on mattresses or had their meals in the other climatic chamber, where the effective temperature was maintained at approximately 86 F (dry-bulb 98 F, wet-bulb 84 F, air speed 200 ft./min—a warm 'mess-deck' temperature), except for about 15 min when they had showers and put on clean shorts. Each man was given salt tablets to replace the salt lost in his sweat, but estimations of urinary chlorides before the third exposure showed a general fall in concentration despite the fact that the salt intake had, on the average, been supplemented already by 11 g of sodium chloride. Extra salt was therefore given before the last exposure.

The average rectal temperatures and half-minute pulse rates before and after work are shown for the three exposures in Table 112. Although the average temperature after work was higher during the evening exposure, the lower temperature recorded after work during the early morning exposure which followed indicated clearly that this was a diurnal effect. The changes in rectal temperature with alternating work and rest were similar for the three exposures. The sweat loss of one subject increased with each exposure; for the other two it diminished. The mean losses for three men were very similar. During the third exposure the subjects were very tired and towards the end of the long rest period they were falling asleep on their stools and their mean pulse rate was higher than in the previous sessions. This was not surprising as they had slept only for 2 to 3 hr in the previous 24, and the work they had carried out corresponded to walking 30 miles or more. Their state of exhaustion at the end of the experiment was in no way indicated by their mean body temperatures and pulse rates, for it was caused by fatigue, not heat incapacitation.

DISCUSSION

The results of these experiments require little amplification or qualification. They apply only to the working conditions described. At these levels of warmth a relatively slight increment in the atmospheric humidity or reduction in the circulation of the air, or additions to clothing such as wearing an overall suit on top of a pair of shorts, may transform a tolerable working environment into one which cannot be tolerated. Fairly wide variations in the air temperature and in the mean radiant temperature of the surroundings may be tolerated more easily. The duration of the exposure is very important. Working conditions which can be endured with relative ease for two hours may cause incapacitation if the exposure is prolonged to three hours. A man who cannot tolerate a hot moist atmosphere as well as his fellows may endure a hot dry atmosphere with greater ease than many of them, and the converse applies. Differences in levels of acclimatization between individuals, or even in the same person from time to time, also affect ability to withstand warm climates. Thus hard and fast rules cannot be applied to defining the upper tolerable levels of warmth and any general recommendations that are made must be regarded as tentative approximations and reasonable margins of safety should always be allowed.

Little has been said, however, of the way in which the environment caused the incapacitation of those who were not able to complete their tasks. None of the subjects lost consciousness completely. Only one man had to retire because of heat cramp. The usual picture suggested peripheral circulatory failure, due to failure to replace, by drinking, the fluid lost as sweat, or to peripheral vasodilatation, with symptoms of dizziness, light-headedness, sluggish mentality, blurred vision, 'pins and needles' in the extremities, headache, abdominal discomfort, nausea or vomiting, or it suggested acute 'hot-climate' fatigue, with complete inability to continue working which was associated with few other symptoms. The step-climbing became less rhythmical. The subjects began to keep time badly, stepping either too quickly or too slowly. Their movements were not well co-ordinated. They stumbled. They paid little attention to the observers, occasionally threw their arms about, and eventually refused, or were unable to go on. If they were at rest, some sat on their stepping stools with their heads on their hands, or lay sprawled on the floor instead of sitting on their stools, unless they were restrained, in marked contrast to their usually alert and well-disciplined attitude. Others were unduly restless and unable to keep still, which was particularly evident when they were being weighed at the end of an experiment.

Irritability was frequent, and outbursts of bad temper or emotional weeping were not uncommon, when men were nearing the limit of their endurance.

Recovery occurred quickly in most cases when a cooler atmosphere was regained. In contrasting this picture with the descriptions of 'heat exhaustion' in the text books, it is important to recall that these subjects were all young men who were well-acclimatized and trained to do step-climbing work at high temperatures; they were encouraged to drink freely (cool drinking water was readily available all the time) and the salt lost in the sweat was replaced after each experiment by the ingestion of salt tablets. Without these precautions the picture of 'acute hot-climate fatigue' might not have emerged so clearly and probably 'heat collapse' or 'heat cramps' would have been encountered more frequently, and there is little doubt that subjects would have succumbed sooner. Recovery was so rapid and so complete that it seems unlikely that cases of uncomplicated 'acute hot-climate fatigue' will be referred often to medical officers in ships or in the hot industries, yet this may well constitute one of the most common ways in which 'heat incapacitation' affects workers in warm environments. It should be included in any comprehensive classification of this group of disorders.

Individual differences were considerable. Some men sweated more freely than others; some flushed more intensely and earlier than others; some were able to drink larger amounts of cool water than others; some became frightened of the heat and obsessed with the idea of getting out of it at any cost when they neared the limit of their endurance, whereas others tolerated it calmly to the point of complete exhaustion. It was the observers' impression that all these men stayed in the warm atmosphere for as long as they could. There were no malingerers.

The 'normal' effective temperatures are included in Table 108 to show that there are pitfalls in using the Effective Temperature Scales to compare the effects of warm working conditions such as were used in these experiments. It is only fair to remark, however, that the Effective Temperature Scales were not primarily constructed for use under the conditions of these experiments—for men working moderately hard for relatively long periods in very warm climates.

The rectal temperature provided a better guide as to whether a man had tolerated a climate well than his sweat loss, although it was by no means infallible.

It seems clear that none of the methods available at the present time for predicting the probability of endurance of extremely warm conditions is satisfactory. The only way to determine with confidence how men will react is to expose them to the conditions in question and see what happens.

Series IX: The Incapacitation of Men at Rest in Hot Humid Conditions

The demonstration that the amounts of cool water drunk by men working in hot humid atmospheres influenced not only the amounts they sweated but also their body temperatures and heart rates raised the possibility that drinking cool water might also influence the length of time for which they could endure hot conditions. In order to find out the lengths of time for which men at rest could tolerate very humid warm air, and to ascertain whether drinking cool water might be a potent factor in prolonging survival, nine of the subjects were exposed to a series of climates with high vapour pressures. Cooling of the skin surface by the evaporation of sweat was entirely, or almost entirely, prevented, for the ambient vapour pressures equalled, nearly equalled or exceeded the vapour pressures which are normally attained at the skin surface. These experiments, and studies made to amplify their results, are described below.

METHODS

In the first experiment the men were observed whilst they were seated at rest and stripped to the waist in an atmosphere at the temperature of the body and saturated with water vapour so that evaporative, radiant and convective cooling were reduced to a minimum (average dry-bulb temperature 99·4°F, wet-bulb temperature 99°F). A few days later the same men were exposed to an air temperature of 130°F with a dew-point temperature of 102°F (wet-bulb temperature of 105°F) which prevented evaporative cooling of the body until the mean skin temperature exceeded 102°F and imposed a considerable convective heat load. Nearly all the subjects retired from this experiment before the effects of drinking cool water could be examined. In view of the difficulties of handling large numbers of subjects under such strenuous conditions the experiment was repeated after several days with the dew-point temperature lowered to 94°F (wet-bulb temperature 100°F). The average air speed on all occasions was 150 ft./min.

All the experiments commenced at 9 a.m. and were completed during the morning. The subjects rested outside the climatic chamber for half an hour before the experiment commenced, entered the test climate, were weighed naked on a man balance, put on their shorts and sat down in canvas-backed chairs. After this, they were only disturbed to change their positions—to equalize the effect of differences in air movement—or to have their body temperatures or pulse rates recorded.

They were encouraged to drink water cooled to within 2°F of 60°F. Their fluid intake and output and changes in body weight during the experiments were recorded. Their pulse rates in the sitting position, pulse rates after standing up for 60 sec, and rectal temperatures (recorded by mercury-in-glass thermometers) were noted before and after the initial rest period and at 30-min intervals during each experiment and shortly before leaving the climatic chamber. Except in the second experiment, the mean skin temperatures were ascertained from measurements recorded at intervals from twelve positions on the body. In this experiment, at air temperature 130°F and wet-bulb temperature 105°F, the subjects had to retire from the climatic chamber in such close succession that there was insufficient time to record the mean skin temperatures satisfactorily.

After each experiment, each subject was given 1 g of sodium chloride, in the form of sugar-and-enteric-coated tablets, for each litre of sweat he had produced during the experiment, and was told to swallow them at intervals during the remainder of the day.

Two of the observers (Subjects 10 and 11, aged 40 and 28 respectively) who were also acclimatized to the tropics and accustomed to work at high temperatures acted as subjects for five additional experiments to enable further measurements to be obtained of the temperature changes which occur in hot humid conditions. In one of these they drank as much as they could, in another they drank only as much as they felt they needed and in a third they wore overalls over their shorts. In these three experiments the dry-bulb temperature was 130°F and the wet-bulb temperature was 100°F. In another experiment the wet-bulb temperature was lowered by 5°F, and in the remaining experiment the air temperature was 99°F and the wet-bulb temperature 97°F, only 2°F lower than in the first experiment in which the other nine subjects took part.

RESULTS

The Effects of Exposure

The times for which the nine men were able to endure these severe conditions are shown in Table 113.

Although none of the men actually lost consciousness whilst in the warm climate, they nearly all remained in the climatic chamber until they were on the verge of collapse and most of them had to be helped to leave. None was fit to do any responsible work. The symptoms were usually sudden in onset, particularly at the higher air temperature (130°F) when most of the men felt quite well until 5 or 10 min before they reached the limit of their endurance. Light-headedness, the feeling that they were going to 'pass out', headache, nausea, vomiting, abdominal discomfort and a compelling desire to get out of the heat 'at any cost' were prominent. Less frequent manifestations were tingling in the extremities, excessive lassitude, hyperventilation, retrosternal pain from breathing hot air through the mouth, and outbursts of weeping. Two men, on the verge of losing consciousness, were unwilling to leave the chamber and protested that they were 'all right' in a manner suggesting the attitude which may be encountered when men are suffering from a lack of oxygen. Restlessness was a prominent feature at times and, even whilst sitting down, some subjects could not control restless movements of their arms, legs and trunk. Many of the subjects (and some of the observers) had difficulty in thinking clearly and quickly, and in answering questions. Only one man experienced severe muscle cramps. All were pleased to lie down and rest for periods varying from 20 min to 2 hr after the experiments ended and to take things easily for the rest of the day, but recovery was usually rapid and uneventful.

The descriptions of the symptoms given by these soldiers were amplified by the subjective and objective observations made when the two observers (Subjects 10 and 11) were exposed to an air temperature of 130°F later. These two men stayed in the heat until they were on the point of collapse. The sequence of events, after they entered the warm atmosphere and sat down stripped to the waist, was first the experiencing of a general sensation of excessive bodily warmth, followed within a few minutes by free sweating from nearly all skin surfaces. The subsequent symptoms were a warm and glowing sensation in the face, and an awareness of the heart beating which gradually increased until the whole body, even the head, throbbed in time with the heart; these were followed by mental 'woolliness' or light-headedness, dizziness, which was sometimes intermittent, epigastric discomfort and, in the case of Subject 10, pronounced 'pins and needles' in the extremities which spread centrally from the periphery. As time went on, features reminiscent of anoxia were often prominent. The subjects, and at times the observers, became poorly orientated in time and wrongly accused the technicians in the air-conditioned observation chamber of not making measurements at the correct times, and of not bringing drinking water as quickly as they might. Time passed very slowly and the measurement of skin temperatures seemed to be a never-ending procedure. The subjects mistook the observers' names, used the wrong words when they spoke and slurred their words. They became either euphoric and talkative or morose, irritable and suspicious and these attitudes sometimes alternated during the same experiment. The writing on their note pads became larger, less distinct and less intelligible and eventually the duty of recording notes had to be turned over to a technician. One of the subjects repeatedly insisted that he was clearheaded and quite fit whilst he was mistaking the names of the observers whom he knew well, and thought the time was an hour later than it was, although he was looking straight at a clock only a few feet away. These mental aberrations, associated with some cyanosis and temporal and circumoral pallor on using the facial muscles, were very suggestive of cerebral anoxia.

Other features were that both these men became increasingly aware of the temperature of the thermo-couple junction used for measuring their skin temperatures, which at times gave rise to burning sensations which were barely tolerable. Subject 10, who suffered severely with 'pins and needles', found that this and the dizziness associated with it could be relieved temporarily by clasping his hands on top of his head and thereby reducing the congestion and swelling of the hands and forearms and returning some of the blood from the periphery. In Expt 6 and 7 he probably prolonged his survival time to some extent by this device.

On the whole, the experience was not really unpleasant until the last few minutes when the feeling of the subjects that they must either get out of the warm atmosphere or collapse was at times overwhelming and frightening. It was easy to understand how this had caused two of the soldiers to run out of the climatic chamber without waiting to report to the observers in Expt 2 and 3.

The rectal temperatures and pulse rates of the nine soldiers, recorded while they were standing just before leaving the climatic chamber, are given in Table 114.

Although in each experiment nearly all the subjects reached the limit of their endurance, the level of the physiological reaction of the group, as gauged by their heart rates and body temperatures, was higher in Expt 2 and 3 when the air temperature was 130°F than in Expt 1 when it was 99·4°F, although the exposure to the warmer climate was shorter.

If the subjects were about to collapse, the medical observer recorded the blood pressure just before or just after they left the climatic chamber, but it was not possible to obtain systematic records. The most frequent observation was an increase in pulse pressure, due to a fall in the diastolic pressure which was sometimes associated with either a rise or a fall in the systolic blood pressure, but marked changes were usually not observed unless a man was near to the limit of his endurance. The impression gained was that significant changes in blood pressure will usually only be observed when collapse is imminent, and that, in the absence of fairly severe dehydration, recovery to normal values will occur quickly when those affected return to a cool atmosphere; but it is clearly desirable to investigate the changes which occur more systematically than was possible on this occasion.

Intense flushing of the skin of the face, neck and body was often observed before incapacitation supervened, and those who first became intensely flushed tended to be incapacitated earlier than the others. Four subjects and one of the observers also developed localised patches of miliaria profunda (sweat duct or gland distensions giving rise to white papular elevations in the skin) which in one case were evident all over the body. The lesions only appeared when the men were nearing the limit of their endurance and faded within 10 min of their leaving the warm atmosphere. None of the men could remember having had prickly heat in the recent past.

Although the salt balance of these subjects was not investigated systematically, routine Fantus tests (1936), carried out on the first specimens of urine passed after the subjects reached the laboratory each morning, suggested that the measures taken to prevent salt deficiency were adequate for the duration of these experiments.

The Relations between Rate of Change of Body Temperature, Rate of Sweating and Rate of Drinking Water

In experiments the intention of which is to examine the relative stresses imposed by different climatic and working conditions not severe enough to incapacitate, useful information can be obtained by comparing the body temperatures, heart rates and sweat losses of the subjects after the same intervals of time in the different conditions. It is not possible to compare the physiological values obtained at the end of the individual experiments shown in Table 115, as the climatic stress for each man varied directly with the duration of the time he had been exposed to the climate. It is possible, however, to compare *the rates at which changes occurred* in the level of the rectal temperatures and in the rates of sweating of the subjects, and to examine the relationships between these and the length of time for which the subjects were able to endure the climates. These rates are shown for the first and third experiments in Table 115 together with the rates at which each man was able to drink cool water.

In nearly saturated air at 99·4°F the relations between the rate at which the men drank cool water and the time for which they could endure the climate, between the rate at which they drank cool water and the rate at which their rectal temperatures rose—the greater the rate of drinking, the slower the rise in rectal temperature—and between the rate at which their rectal temperatures rose and their endurance times, were all highly significant.

In the warmer atmosphere (dry-bulb 130°F, wet-bulb 100°F) the effect of drinking cool water could not be shown because of the short duration of the experiment and the considerable amount of cool water which still remained in the stomachs of the subjects at the end of the experiment. The relation between the rate of rise of rectal temperature for the nine men and the endurance time was again highly significant.

There was no significant relation between the rate of sweating of these men and their endurance time, rate of drinking or rate of rise of rectal temperature in either the first or third experiment. Again, none of these relations was significant for the short second experiment, which terminated precipitately, although that between the rate of rise of rectal temperature and the endurance time only just failed to be significant.

The rate of rise of rectal temperature provided the most satisfactory guide to the relative abilities of these men to endure these warm climatic conditions. Drinking cool water, which retarded the rate of rise of their rectal temperatures, prolonged the time for which they could endure the conditions. This was illustrated well by Subject 3 in Expt 1. He drank cool water steadily in small amounts (250 ml.) at a rate which exceeded the rate at which he was sweating; and the rate at which his rectal temperature rose was the lowest for all subjects. He was so fit at the end of 4 hr that he was able to complete 10 min step-climbing work (mean energy cost 164 kcal.m^{-2}.hr^{-1}) before he left the warm atmosphere.

Changes in Body Temperature

The rectal temperatures of seven out of eight men when they retired from Expt 1 were between 101·4 and 102°F. For five subjects (1, 2, 4, 5 and 6) the rectal temperature increased in a roughly linear relation with time to reach this critical level in 2 hr. Subject 7, who retired after 1½ hr, was a man who developed generalized miliaria profunda and usually exhibited symptoms of heat intolerance before the others.

The mean skin temperature of all the subjects in this experiment rose rapidly to a level just below the air (and body) temperature shortly after they entered the warm atmosphere. After this, in the case of Subject 3 the mean skin temperature remained at or about the temperature of the air and did not follow the rise in rectal temperature. This is shown in Fig. 36. This was also true for Subject 6 and Subject 1 who were both able to drink as much as or more than they sweated (Table 115), although they did not drink nearly as much as Subject 3. In the case of the other subjects the mean skin temperature sooner or later began to rise with the rectal temperature. When this happened heat incapacitation followed fairly soon.

The serial changes in the mean skin temperature and rectal temperature could not be ascertained satisfactorily during the brief second and third experiments. These changes were, however, recorded later under similar conditions with Subjects 10 and 11 and the effects of varying the conditions were explored tentatively. The serial changes in body temperature of these two men, which were similar to those of the other nine men but more informative, are plotted in Fig. 37 and their water intake and sweat losses are given in Table 116.

The dew-point temperature in Expt 4 and 5 (94°F) was probably above the mean skin temperature of the subjects at first and evaporative cooling was prevented. Shortly after they entered the climatic chamber, however, the men began to sweat freely and their mean skin temperatures rose above 100°F, so that the gradients between the vapour pressures of the air and at the skin surfaces were reversed and evaporative cooling was allowed to take place. This modified the slope of the rise in the mean skin temperature and partly offset the effects of convective and metabolic heating until the deep body temperature (rectal temperature) reached the level of the mean skin temperature, when it was no longer possible for the body to control its temperature within acceptable limits and symptoms of heat incapacitation supervened.

In Expt 5 the men drank only the amounts of water they felt they needed and both endured the conditions longer than in Expt 4 (Table 116) when they drank as much as they could. Furthermore, Subject 10 sweated more although he drank less, and Subject 11 sweated about the same amount although he drank much less. This suggests that the sweat output is independent of water intake

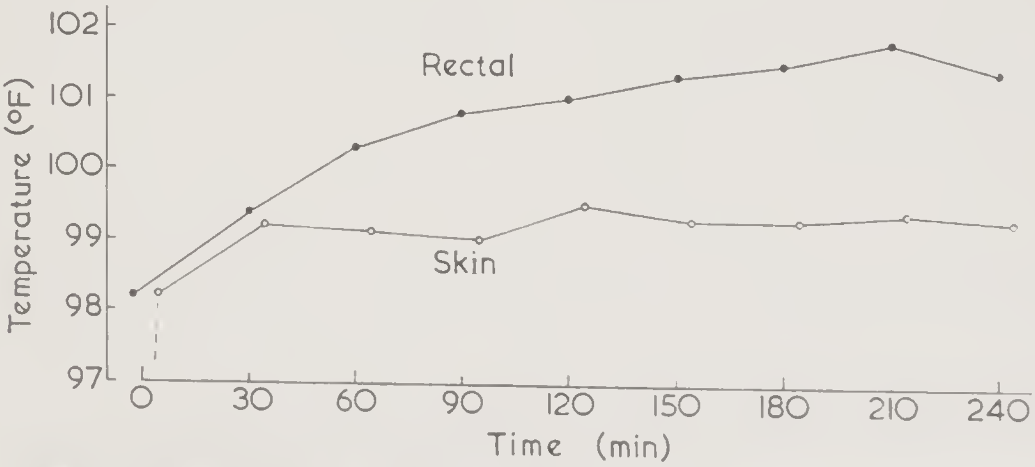

FIG. 36. Series IX. Changes in skin and rectal temperature in Subject 3 resting seated in saturated air at 99·4°F.

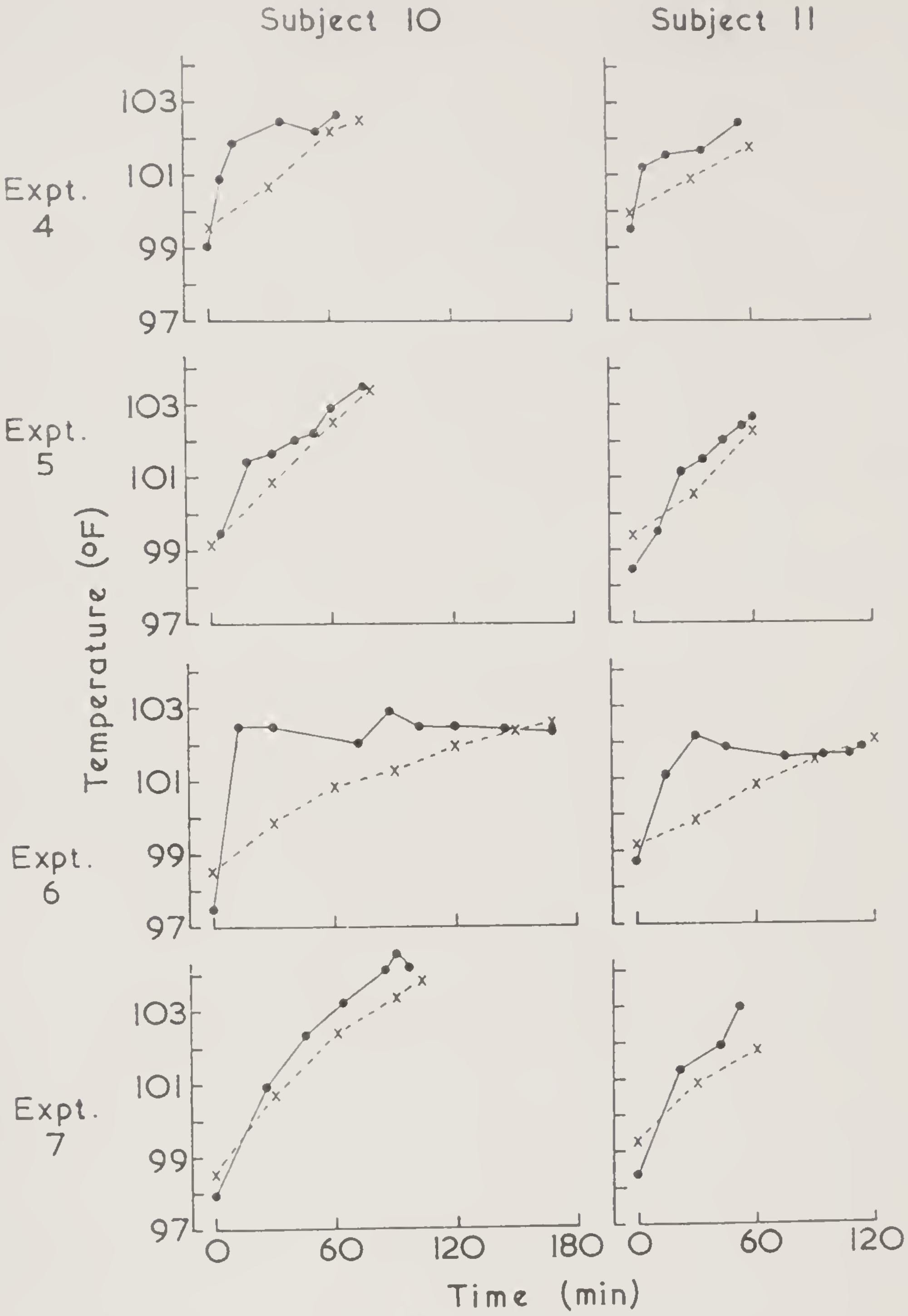

FIG. 37. Series IX. Mean skin (●) and rectal (×) temperature in Subjects 10 and 11 in Expt. 4 to 7. The environment was dry-bulb temperature 130° F, wet-bulb 100° F, air speed 150 ft./min except in Expt. 6 when wet-bulb 95° F was used. Overalls were substituted for shorts in Expt. 7.

when the latter is forced beyond the physiological requirements, as it was in Expt 4.

The importance of the vapour pressure gradient for efficient evaporative cooling was shown clearly in Expt 6. When the dew-point temperature was lowered to 87° F (wet-bulb temperature 95° F) under conditions which were otherwise identical with those of Expt 4 and 5, this permitted evaporative cooling of the skin surface from the outset. The mean skin temperature was again raised almost immediately by the high air temperature (130° F) to a level which was consistent with maximal evaporative cooling and efficient body temperature control (101–102° F), where it remained until the deep body temperature reached or exceeded the level of the mean skin temperature and symptoms of heat incapacitation again supervened.

When these two subjects wore overalls, in Expt 7, the extra clothing obviously interfered with evaporative cooling of the skin and their mean skin temperatures rose to higher levels than when they were not wearing overalls. Subject 11, who was not able to endure the climate as long as when he was stripped to the waist, was recovering from a cold, so the results of this experiment were inconclusive.

The last experiment in which these two men took part is not illustrated in Fig. 37. It was carried out at rest with the air temperature at 99°F and the wet-bulb temperature at 97 F, only 2 F less than it was in Expt 1. Both subjects were able to endure this climate for 4 hr and to complete 10 min step-climbing work (mean energy cost 164 kcal.m $^{-2}$.hr $^{-1}$) in the warm atmosphere at the end of this time. These conditions were subjectively much less pleasant to endure than when the air temperature was 130 F although they could be tolerated longer. The serial changes in the rectal and mean skin temperatures were very similar to those of Subject 3 in Expt 1 (Fig. 36).

DISCUSSION

The observation of Blockley and Taylor (1948) that men in 'union suits' (overalls) may withstand dry air at 240 F for between 20 and 30 min, and the observation made here that men both stripped to the waist and wearing overalls can withstand air at 130°F for only a few minutes longer if the humidity is so high that evaporative cooling of the skin surface is interfered with, indicate that the moisture content of the air is of vital importance to survival at high temperatures. This is emphasized further by the considerable increase in the survival times of Subjects 10 and 11 in Expt 6 in which the conditions were the same as in Expt 3, 4 and 5, except that the wet-bulb was lowered from 100°F to 95 F, by the increase in survival times between Expt 2 and 3 when the wet-bulb temperature was lowered from 105°F to 100°F, and by the relative ease with which Subjects 10 and 11 survived dry-bulb 99°F, wet-bulb 97 F for 4 hr although eight out of nine of the other subjects had succumbed to dry-bulb 99·4 F, wet-bulb 99°F within a much shorter period.

Expt 1, 2 and 3 were designed to reduce evaporative cooling to a minimum so that the profuse sweating which occurred was valueless in controlling the body temperature and in assisting survival. It was not surprising to find that the sweat rates of the subjects were unrelated either to their endurance times or to their ability to drink. The close relations which were found between the rate of drinking cool water and both the rate of rise of deep-body temperature and the length of the survival time in Expt 1 suggest that the temperature of the drinking water may be important, as well as the amount of water which is drunk. Apart from its cooling effect, cool water is more palatable to the majority of people than tepid water, and they will wish and be able to drink more of it for this reason.

The value of cool drinking water to those who have to work in extremely warm environments cannot be emphasized too strongly, in view of the die-hard opinion which is still encountered that drinking cool water will cause disturbances of the alimentary tract. In several thousand experiments at Singapore no ill effects were observed from drinking cool water. A man is usually the best judge as to whether his drinking water is too cool. If it is, he will wait until it warms up to the temperature which he prefers. The temperature of the water used in these experiments, 60°F, which was imposed by the technicalities of ensuring that the subjects received it at a constant temperature, was rather lower than is suggested for normal use. No ill effects resulted when the men drank it, but 70°F would have been a more suitable temperature.

Although the object of these experiments was not to investigate the clinical features of heat incapacitation, the symptoms and signs have been described at some length, as it is unusual for these to be reported when the victims are healthy young men who recover quickly. Although complete recovery is to be expected if it is possible to obtain quick relief from the warm atmosphere, nevertheless incapacitation is complete when it does occur and will cause a break-down in any operation on which a watch-keeper or industrial worker may be engaged. Moreover, acute hot-climate fatigue, both mental and physical, may impair efficiency for a considerable time before physical incapacitation occurs. The most useful prognostic sign for indicating whether or not a man is withstanding the climate well is the rate of rise of his body temperature. Any measures which can be taken to reduce the rate of rise of body temperature will prolong the time for which a man will be able to endure excessively warm climatic conditions and will increase his fitness and efficiency during this time.

Summary

1. The ninth series of experiments at Singapore (Series IX) dealt with three topics: the effect of water intake on men working in the heat, the upper tolerable levels of warmth for acclimatized men in the tropics, and the incapacitation of men at rest in hot humid conditions.

2. The experiments on water intake were performed during the artificial acclimatization of the subjects in which they were exposed to increasing degrees of heat stress in preparation for the investigation of the upper tolerable levels of warmth. The men were supplied with cool drinking water at the rate of 550, 700 or 850 ml. per hour during exposure to hot conditions, and their sweat losses, body temperatures and pulse rates were observed.

3. The results showed that those receiving the greatest amount of water produced the greatest amount of sweat, and those receiving the least water, the least sweat. The effect became more marked with the passage of time. During the first hour there was no difference between the groups but during the second hour a difference became apparent and this became more marked during the third and fourth hours. A comparable effect on body temperature was observed—those receiving the least water had the highest rectal temperatures and those receiving the most water had the lowest rectal temperatures. A similar, but less well marked, effect was observed on the pulse rate, those receiving the most water exhibiting the lowest pulse rates.

4. The results also showed that the amount of sweat secreted is in part dependent on the amount of water drunk, and emphasized the importance of the provision of adequate amounts of cool water for men exposed to heat.

5. In the experiments on the upper tolerable levels of warmth, the subjects were exposed to the test conditions on alternate days 3 days per week and on the remaining days they exercised in a less strenuous environment. During the test exposure the subjects followed the 'Queen Square Routine' for working

subjects; they wore overalls over cotton shorts and the air speed was kept constant at 150 ft./min.

6. It was found that when the air temperature was 100°F or less, the wet-bulb temperature above which some men were incapacitated was 92°F. Above dry-bulb temperature 100°F the wet-bulb temperature that could be tolerated was lowered approximately 1°F for every 10°F rise in air temperature. Very small changes in the wet-bulb temperature had a profound effect at these critical levels of warmth. Similarly, reducing the air speed from 150 ft./min to 20 ft./min converted a readily tolerated into an intolerable environment.

7. The effect of radiant heat on upper tolerable levels was not so profound. At dry-bulb 115°F, wet-bulb 90°F, and air speed 150 ft./min, increasing the mean radiant temperature by 39°F had an effect equivalent to that of wearing overalls over shorts instead of shorts alone.

8. The duration of the exposure was important. Conditions which were tolerable for 100 min proved to be intolerable for 160 min. Repeated exposure during a twenty-four hour period did not impair the ability of these fit young men to tolerate hot conditions. They recuperated in a cooler atmosphere in which they did not sweat so freely and were able to replace their salt and water losses.

9. In the third part of Series IX, in order to determine the lengths of time for which men at rest could tolerate very humid warm air and to ascertain whether drinking cool water might prolong endurance to such conditions, nine men were exposed to a series of climates with very high water-vapour pressures in which they sat at rest stripped to the waist. The air speed was 150 ft./min.

10. When the dry-bulb temperature was 99·4°F and the wet-bulb 99°F, the average length of endurance was 144 min. The first man retired at 79 min; the last man withstood the conditions for 240 min, and then was able to complete 10 min step-climbing.

11. When the dry-bulb was 130°F and the wet-bulb 105°F the average endurance time was 37 min (range 30–55 min). At the same dry-bulb but at wet-bulb 100°F the average endurance was 55 min (range 34–129 min).

12. In the first and third experiments the endurance times of the subjects were closely related to the rate of rise of their rectal temperatures. In the first experiment there was also a close relation between the rates at which they were able to drink cool water, their endurance times and the rate of rise of their rectal temperatures.

13. When two other acclimatized men were exposed to dry-bulb temperature 99°F, wet-bulb 97°F, they endured the conditions for 4 hr and were able to complete 10 min step-climbing at the end of this time. When the air temperature was 130°F and the wet-bulb 95°F one man survived for two, and the other for nearly three, hours.

14. The main symptoms of approaching collapse and the changes observed in skin and rectal temperature are described. It was observed that serious impairment of judgment, reasoning and perception frequently preceded physical incapacitation, and it is stressed that adequate allowance must be made for this mental impairment when assessing the permissible levels of environmental warmth to which men may be exposed.

CHAPTER 9. ANCILLARY INVESTIGATIONS IN SINGAPORE

An account of the work of J. M. Adam, F. P. Ellis, Helen M. Ferres, J. W. Jack, R. T. John, D. E. Lee, J. W. H. Lugg, R. G. Scott MacGregor, R. K. Macpherson, P. S. B. Newling, T. B. Yap and P. S. You

The preceding chapters have given an account of the main stream of the work in physiology done at Singapore—that which was necessary to complete the programme originally envisaged by the Climatic Efficiency Subcommittee of the Royal Naval Personnel Research Committee. This work was, however, by no means all that was done in the four years of the Unit's existence; the Unit engaged in a number of other activities, the diversity of which makes their description somewhat difficult. Some were the necessary extensions of the main body of work (an example of this was the measurement of mean radiant temperatures by means of metal model men); some arose from chance observations during the course of the systematic experiments; some were the fruit of the close association with the University of Malaya; some may be described as logical extramural extensions of the general theme of the work, and others were *ad hoc* investigations which devolved upon the Unit by virtue of its nature as a quasi-military establishment.

Included in the last category were the investigations of conditions in warships during naval exercises by teams of workers from the Unit under the direction of Surgeon Commander Ellis. These investigations, which have been described in confidential reports to the appropriate authorities, may prove to be among the more important of the Unit's activities.

There were also other useful but minor activities which were performed by the Unit largely because it possessed the necessary personnel and equipment to deal with the problems concerned. An example was the testing of the Higgins Solar Still in the Johore Straits (Lind & Rusbridger, 1952). These small investigations often provided information of physiological interest and one, the testing of jungle uniforms, will be described at some length.

THE PHYSIOLOGICAL EFFECTS OF WEARING JUNGLE UNIFORMS

This work, which was described in full in a report to the Royal Naval Personnel Research Committee (Adam, Jack, John, Macpherson & You, 1951), is of interest partly for the physiological observations that were made but chiefly because it demonstrates the limitations of physiological methods when applied to such problems as that of assessing the relative merits of articles of clothing.

Reports by the Far East Land Forces of 'user trials' on uniforms of gaberdine in hot wet climates had stated that the material was unsuitable for tropical use owing, it was thought, to the high degree of water-repellency of the suits tried. Some years previously, as the result of an investigation on the 'mosquito-proofness', physical characteristics and physiological effects of eleven different fabrics, the workers at the National Hospital had reported that scoured (non-water-repellent) Utility Gaberdine 3170 was the most suitable fabric for the uniforms of service personnel in hot wet climates. In consequence of these findings, the War Office made a formal request to the Unit to undertake laboratory trials of eight uniforms of gaberdine which had been scoured so that they exhibited the minimum degree of water-repellency. The intention was that if the report on these trials was favourable, user trials of the scoured gaberdine would be undertaken, whereas if the report was unsatisfactory the search for a suitable material would be continued. It was requested that the trials should provide an adequate comparison of these garments with the existing issue of jungle uniform and, further, that the methods employed by the National Hospital workers should be followed as closely as possible in order that the findings in London and in Singapore should be readily comparable. Later, a further request was received that the comparison should include American-type uniforms of 5 oz poplin.

The National Hospital workers, in reporting on the fabrics tested by them, had stated with respect to the physiological effects that 'there was no significant difference between any of the fabrics and the control'. It was thought, when the present experiment was being planned, that this might again be the finding, but it was also thought that the experiment might provide a valuable opportunity of assessing the usefulness of physiological methods for determining the suitability of tropical clothing.

The final plan of the experiment was to compare the physiological stresses imposed by working in a hot humid climate in three different types of clothing—the current issue of jungle uniform (olive-green cellular bush jacket and olive-green drill trousers), the uniform of scoured gaberdine, the American-pattern uniform of 5 oz poplin—and no clothing at all.*

The subjects were tested wearing each of the four types of clothing, both by itself and with full webbing equipment including pack, haversack, water-bottle, etc., the weight of the pack being so adjusted that the entire assembly was equal to one third of the subject's nude body weight.

The eight subjects, and one reserve, were Army volunteers who received a preliminary period of training and acclimatization extending over 2 weeks (12 working days). The test environment represented very hot jungle conditions —dry-bulb temperature 95°F, wet-bulb temperature 85°F and air speed 20 ft./min. The experimental design was a complex arrangement of Latin squares.

The results were in one sense definitely conclusive; they distinguished clearly between wearing any uniform and wearing no clothing at all. No significant difference could be found, however, between the physiological effects of the several uniforms—in the sweat losses, the body temperatures or the pulse rates—although, when the subjects' views on the relative merits of the uniforms were sought (in questionnaires given at the conclusion of the tests), opinion was found to be divided as to whether the best was the scoured gaberdine or the American 5 oz poplin. There was, however, unanimity of opinion that the least satisfactory was the existing issue of cellular bush jacket and drill trousers. These opinions accorded well with those of the observers, who considered that the existing issue imposed a greater stress on the wearer than either of the other two types. It was also clear to all that wearing any type of clothing under the conditions of the experiment imposed a greater strain than wearing no clothing at all.

The reason advanced by the wearers for their dislike of the current issue was that it was 'uncomfortable' and, more specifically, that it was hot, heavy, rough and irritating to the skin and adherent to the body when wet. The contrary virtues of coolness, lightness, softness and non-adherence when soaked with sweat were attributed to the preferred one of the other two suits.

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* In fact, the men wore brief light calico shorts which constituted a close approximation to nudity.

This suggested that the physical characteristics of the uniforms might provide the explanation of the preferences expressed by the subjects, and that attention should be turned to the behaviour of the suits in hot conditions, rather than the physiological reactions of the men who wore them.

Among the physical characteristics examined was the amount of water taken up by the clothes when they were thoroughly soaked, and the subsequent rate of drying. These characteristics are of importance because in the tropics uniforms may become wet not only with sweat but also with rain and river water. In fact, under jungle conditions, clothing may be as often wet as dry, and the additional weight which has to be carried when it is wet may be of significance. The rate of drying is important, because even if a wet suit is not a serious handicap during warm daylight hours, it becomes intolerable to sleep in at night.

The behaviour of these garments when thoroughly soaked and hung up to dry conformed to expectations. The amount of water taken up was, in every case, close to the dry weight of the garment, which meant that the heavier a garment the more water it held, and this was to a large extent independent of the type of material from which it was made. When wrung out and hung up to dry, there was at first a short period of rapid weight loss, due to dripping, followed by a slower rate of loss as the material dried. This slower rate of loss of weight was the same for all garments, which meant that the heavier a garment the longer it took to dry. As the weight of the garment approached its dry weight the weight-loss curve flattened out very markedly. At this stage the garment was dry except for pockets, seams, and other areas of special thickness.

The current issue of uniform was heavier than the others and, therefore, absorbed more water and took longer to dry, and the drill trousers of this uniform absorbed more water and took longer to dry than any other garment. The complaint of the subjects that the current issue uniforms were inferior because they were heavier, especially when wet, appeared to be well founded.

When, however, attention was directed to the amount of sweat absorbed by the clothes during the experiment, a more complex state of affairs was revealed. In order to measure the sweat loss of the subjects, they were weighed naked at the beginning of the experiment and their clothes were also weighed. At the conclusion of the experiment the subjects were weighed again (the difference in the two weights giving the amount of sweat lost) and their clothing was also re-weighed. (The gain in weight in the clothing represented that part of the sweat loss which failed either to evaporate or to drip on the floor.) As has been implied in the statement that there was no difference in the physiological effects of the several suits, the total amount of sweat lost was the same for all suits. Furthermore, the amount of sweat absorbed was the same for all the uniforms. (This does not imply that the amount effectively evaporated was the same, as observation seemed to show that there was a greater loss by 'drippage' in the case of the current issue). When, however, the amount of sweat absorbed by the component parts of the uniforms and equipment was examined it was seen that, despite their greater weight and hence their potential capacity for absorbing water, the trousers of the current issue did in fact absorb the least of all; the difference was almost entirely accounted for by the gain in weight of the boots and socks. It appeared, then, that the sweat, instead of being absorbed by these trousers, ran down the legs into the boots where evaporation was impossible, and consequently made no contribution to the loss of heat.

The conclusions drawn were that the physiological methods used were unsuitable for the purpose for which they were intended. It is likely that real differences did exist between the effects of the various uniforms, although no measurable difference was found in the physiological reactions. That is not to say that suitable physiological criteria for assessing the stress of clothing may not be devised in the future; but at present physical tests, correlated with carefully controlled 'user trials', offer the best hope for the appraisement of the suitability of articles of clothing.

THE MEASUREMENT OF RADIANT HEAT

Of the experiments conducted at the National Hospital, the least satisfactory were those made to determine the physiological effects of added radiant heat. This was undoubtedly due to the limitations imposed by the time and equipment available. The series of experiments planned for this purpose at Singapore therefore assumed an added importance, so that great care was taken to ensure that the equipment provided was adequate, and a specially designed radiant-heat tunnel (described in Chapter 6) was built for use in these experiments.

Experiments designed to measure the physiological effects of added radiant heat require *a priori* the measurement, or definition of the magnitude, of the radiant-heat stress applied to the subjects. This can be done either in terms of the mean intensity of radiation or, as is preferable, in terms of the mean radiant temperature of the surroundings.

The concept of a 'mean radiant temperature' which is due to Barker (1931) and Bohnenkamp & Pasquay (1931) is particularly useful in dealing with those cases in which, as usually happens, the surroundings differ in temperature and in emissivity from place to place. It may be defined as that uniform temperature at which a black surface would radiate with an intensity equal to the mean observed, or as that temperature required by the surroundings if they were uniformly black to produce the intensity of radiation existing at the point of measurement.

Bedford and Warner (1934) had shown that the globe-thermometer used by Vernon to measure 'Effective Radiation Temperature' (Vernon, 1932), could be used to measure mean radiant temperature. However, as in non-uniform surroundings this will vary from place to place it remained to be shown to what extent the mean radiant temperature as determined by the globe-thermometer represented accurately the mean radiant temperature to which a large irregularly shaped object such as a man might be exposed. Dr. Ezer Griffiths, F.R.S., and Mr. M. J. Hickman of the National Physical Laboratory therefore devised a method using life-sized metal models of men which enabled not only the determination of the mean radiant temperature as applied to a man but also the direct measurement of the total amount of radiant heat exchanged by a man when exposed to a given environment. The models are illustrated in Fig. 38 together with the control panels by means of which the total electrical energy input was adjusted and measured and their temperatures determined. These models were used in conjunction with the radiant-heat tunnel to measure the radiant-heat load on the subjects used in the physiological experiments described in Chapter 6 and the findings, from which this account is taken, were reported to the Royal Naval Personnel Research Committee (Newling, 1954).

There were two pairs of models, one pair representing men standing and the other pair men sitting. The members of each pair were identical in all respects, except that the surface of one was matt black with an emissivity close to unity, and the other had a highly polished surface with a very low emissivity. Disposed throughout the interior of each model was an electrical heating system, and fans were fitted to ensure that the heating was as uniform as possible. Attached to the interior surface at fifteen representative points were thermocouples which enabled the temperature to be determined accurately.

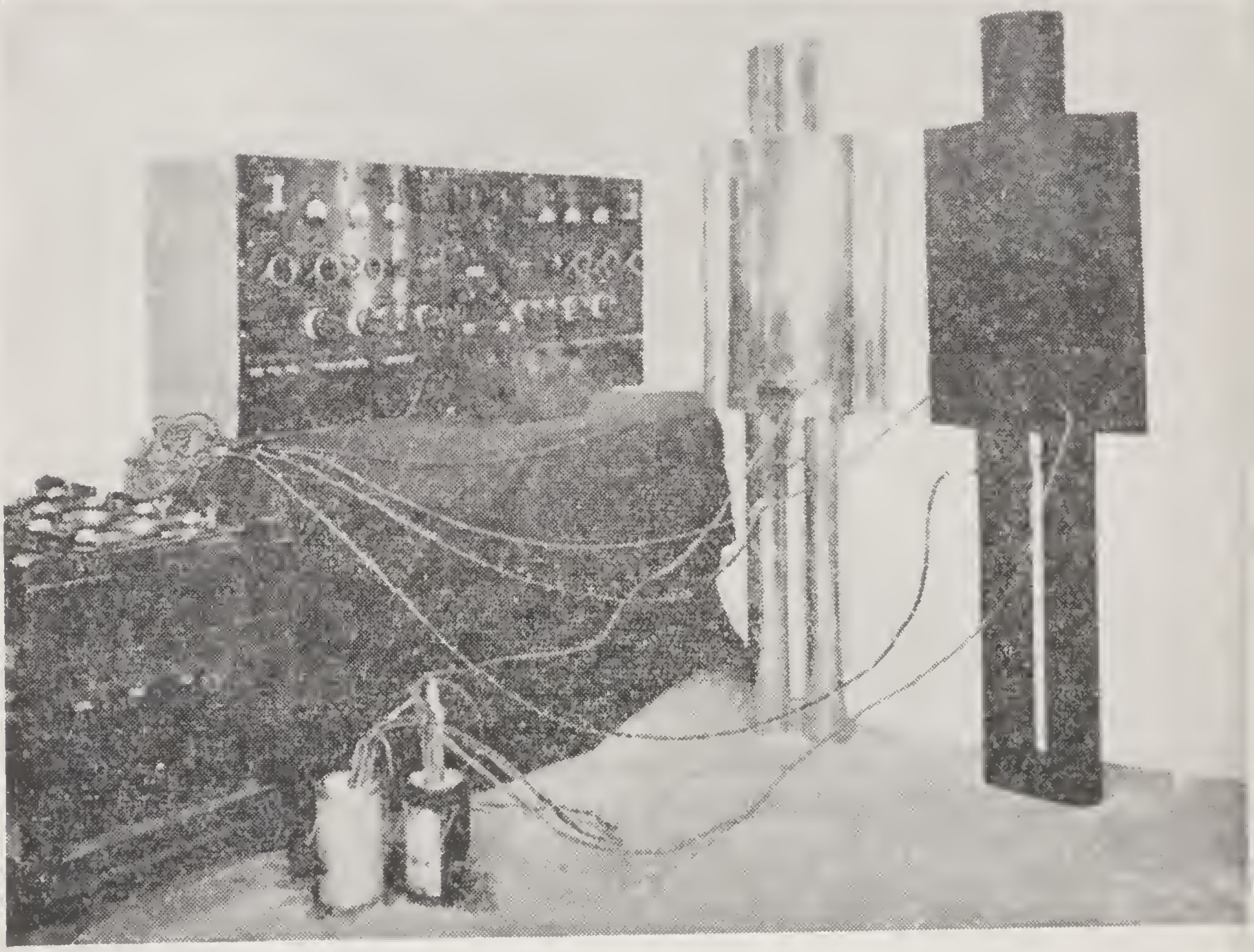

FIG. 38. Measurement of radiant heat. The control panel and the standing polished and black metal model men.

When used to determine the radiant-heat load, the models were employed as follows. With the panels of the radiant-heat tunnel adjusted to the desired value, the black member of a pair was exposed in the tunnel until its temperature as measured by the thermocouples became constant. It was then removed and, care being taken to keep the panel temperatures, the air temperature and the wind speed at their previous values, the polished member of the pair was introduced and similarly allowed to come to equilibrium. Then, by means of its internal heaters, power was supplied to this model until the surface temperature reached that reached by the black member when in equilibrium. The amount of power supplied represented the heat gain of the blackened model by radiation, the convection exchanges for the two models when their temperatures were the same being equal.

To determine the mean radiant temperature of the surroundings for men, the procedure was as follows. The mean radiant temperature at the centre of the radiant-heat tunnel was first assessed approximately, using a globe-thermometer. The globe-thermometer was then replaced by a black model, which was then heated until its temperature was that previously determined as the mean radiant temperature. The black model was then replaced by the polished member of its pair and this was brought to the same temperature. The power that had been supplied to the two models was then compared. If the same amount of power was supplied in both cases, the temperature of the models was taken to be equal to the mean radiant temperature of the surroundings, as all the heat exchanges were identical for the two models. If the power supplied to the black model was greater than that supplied to the polished model, it was inferred that their temperature was above the mean radiant temperature of the surroundings. If the power supplied to the black model was less than that supplied to the polished model, it was inferred that their temperature was below the mean radiant temperature of the surroundings. The mean radiant temperature was thus found by a process of trial and error.

Two other ways of determining the mean radiant temperature of the tunnel were also available. The first was by calculation—by measuring the temperature of the surrounding walls directly and, from a knowledge of their emissivity, summing their effects. The second way was by scanning the surroundings with a thermopile.

The calculation by direct measurement of the temperature of the surroundings proved in practice to be almost impossible. Only four of the surfaces (roof, floor and two sides) were heated in the radiant-heat tunnel; the two open ends were at air temperature. The open ends were represented by a variety of materials with correspondingly varying emissivities, and in the tunnel itself the position was complicated by the fact that the floor was protected by an open-work grill which provided a surface for the subjects to walk on, and the side walls were also obscured in part by metal guards which prevented contact with the hot surfaces.

It was possible, however, to measure the mean radiant temperature in the three remaining ways, using the metal models, the globe-thermometer and the thermopile, and to compare the results.

With the floor grid and side screens in position, the mean radiant temperature at a height of 3 ft. 9 in. was measured on seventeen occasions with a globe-thermometer and with a thermopile. With the thermopile, eighteen readings were taken in three planes at right angles on each occasion. The average difference between the mean radiant temperature as measured by the globe-thermometer and the air temperature was found to be 11·9°F and that between the mean radiant temperature as measured by the thermopile and the air temperature, 20·5°F. This represented a very large discrepancy between the results of the two methods of measurement.

It was not to be expected that the mean radiant temperature determined by a thermopile or by a globe-thermometer, which measure the temperature at a point, would agree with the mean radiant temperature as determined for a large and irregular object, such as a metal man, when measured in a non-uniform environment. It was found, however, as can be seen from Table 117, that if three globe-thermometers were suspended at heights of 2 ft., 3 ft. 9 in. and 5 ft. 6 in. from the floor and the arithmetical mean taken of the mean radiant temperature measured by each of them, this mean value was in very close agreement with the value obtained by using the metal men. This finding is of particular significance because it means that in situations where the use of a large and complex device is impossible, a reliable value for the mean radiant temperature as applied to men can be obtained by the use of three globe-thermometers. It should be noted, however, that although the determinations were made in non-uniform surroundings, this conclusion does not apply to the special case in which it is desired to measure the mean radiant temperature in a situation when the chief source of heat is from a high-temperature point, such as an open furnace door.

It was concluded from these experiments that:

(a) if the variation in the mean radiant temperature over the space occupied by a man is less than 2°F, a globe-thermometer in one position will measure this temperature sufficiently accurately to indicate the effect of radiant heat on the man;

(b) if the variation of the mean radiant temperature is more than 2°F, measurements in more than one position may be necessary;

(c) the globe-thermometer should be left in position until successive readings taken at 10-min intervals do not differ by more than 1°F.

This last point was made as it was found that, whereas the usual expected time was 20 min, in these experiments the globe-thermometers often took as long as 45 min to come to equilibrium.

The agreement between the mean radiant temperature as measured by the globe-thermometer and as measured by the metal men is in contrast with the discrepancy observed between the values obtained from the globe-thermometer and those from the scanned thermopile. It is thought that this discrepancy is due to the fact that with the thermopile at least 60 exposures would have been required to scan the whole environment; the eighteen readings made on each occasion did not provide an adequate measure of the variability that existed.

The results of the measurements made to determine the amount of radiant heat gained by the models are summarized in Table 118; from these it can be deduced that the equations describing the heat gained by (a) the standing model and (b) the sitting model are

$$\text{(a)}\quad Y = 6{\cdot}1(T_r^4 - T_s^4)10^{-9}$$

$$\text{and (b)}\quad Y = 4{\cdot}9(T_r^4 - T_s^4)10^{-9}$$

where Y is the heat gained measured in watts, T_r is the mean radiant temperature and T_s is the mean surface temperature of the model, both measured in degrees Fahrenheit absolute.

If it can be assumed that the emissivity of human skin is close to unity and that the skin temperature remains constant, the increase in the amount of heat gained by the human body for an increase of 1°F in the mean radiant temperature will depend on the mean radiant temperature. For example, an increase in the mean radiant temperature from 90°F to 91°F will decrease the amount of radiant heat lost by a standing man by 4·1 watts* and that lost by a sitting man by 3·3 watts, and an increase in the mean radiant temperature from 125°F to 126°F will increase the amount of radiant heat gained by a standing man by 4·9 watts and that gained by a sitting man by 3·9 watts.

The men whose sweat losses were measured in the physiological experiments on the effects of radiant heat described in Chapter 6 spent 110 min standing in the tunnel and 95 min sitting in the tunnel during experiments in which the mean radiant temperature varied from 90°F to 126°F. The effect of increasing the mean radiant temperature by 1°F on their sweat loss (measured in grams per kilogram of their body weight) would be expected to vary between

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* 1 watt = 0·014 kcal/min

$(110 \times 4{\cdot}1 + 95 \times 3{\cdot}3) \times \dfrac{0{\cdot}014}{60 \times 0{\cdot}56}$ g at the lower level of mean radiant temperature and $(110 \times 4{\cdot}9 + 95 \times 3{\cdot}9) \times \dfrac{0{\cdot}014}{60 \times 0{\cdot}56}$ g at the higher, if it is assumed that the latent heat of vaporization of sweat is 0·56 kcal/g and that a man of the same size as the models would weigh 60 kg. Thus the expected variation is between 0·32 g and 0·38 g. This is in agreement with the increase in the amount of sweat lost per °F rise in the mean radiant temperature of the surroundings observed in Series VI and VII—0·32 and 0·31 g/kg respectively (see pp. 109, 114).

These metal models could also be used to calculate the convective heat lost by a man in a hot environment. When the temperature of the models was equal to the mean radiant temperature there was no exchange by radiation and, as the models did not sweat, there could be no heat loss by evaporation. The convective loss was found to conform to the equation

$$H = 0{\cdot}61\, T\sqrt{V}$$

where H is the heat lost (kcal. m^{-2}. hr^{-1}), T is the difference between the model surface temperature and the air temperature (°C), and V is the air speed (ft./min). This may be compared with the equation

$$H = 0{\cdot}53\, T\sqrt{V}$$

derived by Nelson *et al.* (1947) for the human subject.

THERMAL COMFORT

The best example of the logical extramural extension of the Unit's activities is to be found in the investigation by Surgeon Commander Ellis of thermal comfort, for both naval ratings afloat and civilians ashore. This work has been reported in full to the Royal Naval Personnel Research Committee (Ellis, 1951*a*, *b*, 1952*a*) and the main findings subsequently published (Ellis, 1952*b*, 1953*b*). The value of the observations is such, however, that a brief account of the major findings is given here.

Much attention had been directed towards establishing upper tolerable levels of warmth, but it was clearly understood, and especially emphasised by the experiments described in Chapter 8, that efficiency, even in the simplest tasks, would decline before the limits of tolerability were reached. It was also appreciated that continuous exposure to conditions which produce feelings of discomfort, even though the discomfort is felt to only a minor degree and may not be accompanied by a measurable fall in efficiency, will lead to discontent and behavioural problems in the Services and to unwillingness to continue under such conditions by civilians. It is for these reasons that the studies by Surgeon Commander Ellis on thermal comfort are of such value.

The first series of observations (Experiments 1 and 2), on ratings aboard ship in the tropics, was made during two voyages between Singapore, Hong Kong and Japan in an aircraft repair ship. Copies of the 'Comfort vote slip', which is reproduced below (p. 188), were distributed to the men on the mess-decks and while the men were filling them in observers measured the wet- and dry-bulb temperatures, the globe-thermometer reading and the air speed (by means of a kata-thermometer) at several representative points.

The 'comfort vote slip' inquired into four things: the degree of comfort felt, whether perspiration was present, the amount of clothing worn, and the air movement perceived. The comfort scale was derived from that previously used by Bedford (1936, 1948).

The voyages provided reasonable variation in the temperatures experienced, although no really cold conditions were met with. The clothing worn was largely a matter of preference by the individuals; if they found the environment uncomfortably warm they removed their shirts. (In computing effective temperatures, the 'Basic' Scale was used for men stripped to the waist; otherwise, the 'Normal' Scale was employed.)

Comfort vote slip

Compartment .... Name Date

I. Put a cross against the words which describe your sensation of comfort in relation to the temperature conditions in this compartment at the present time.

1. Much too warm.	
2. Too warm.	
3. Comfortably warm.	
4. Comfortable.	
5. Comfortably cool.	
6. Too cool.	
7. Much too cool.	

II. Put a cross in the following table against the line which describes most accurately the air movement you feel whilst answering these questions.

1. 'Still air'. No movement perceptible.	
2. Slight air movement. Only just perceptible.	
3. Moderately good air movement. Easily perceptible. Gentle breeze.	
4. Very good air movement. Highly perceptible. Strong breeze.	

III. *Perspiration.* Are you *wet* with perspiration on your face or chest at the time of answering this questionnaire?

Answer

IV. *Clothing.* Are you stripped to the waist?

Answer

The results of these enquiries are summarized in Tables 119, 120, and 121. From these, two interesting findings emerge. The first is the relatively clear-cut nature of the results, as exemplified in Table 119, and the second is the agreement between the occurrence of sweating and the prevalence of discomfort as exemplified in Tables 120 and 121. When comfort was used as the criterion, the upper acceptable level of warmth was defined as that below which more than 80 per cent of the men declared that they were within the zone from 'comfortably cool' to 'comfortably warm'. For the two experiments separately, this level was at effective temperatures of 80° F and 79° F; if the results of the two investigations were combined, it was at an effective temperature of 79° F. When the occurrence of sweating was used as the criterion, the upper acceptable level of warmth was defined as that below which less than 20 per cent of subjects reported that they were wet with perspiration. For the two investigations separately, this was at effective temperatures of 79° F and 78° F; when the two investigations were considered together, it was at an effective temperature of 78° F. Other conclusions of importance were that more than 80 per cent of the subjects were stripped to the waist when the effective temperature exceeded 80 F and less than 20 per cent were stripped to the waist when the effective temperature was below 68 F.

These findings are very consistent and emphasize that even for fully acclimatized people not engaged in strenuous exercise and wearing the minimum of clothing an effective temperature of 78°F should not be exceeded if some of them are not to be uncomfortably warm. The effects of variations in air movement showed that increasing the air speed greatly increased the proportion of those who felt comfortable above dry-bulb 85 F, whereas all subjects were reasonably comfortable, whatever the air speed, below dry-bulb 83 F. The incidence of observed sweating was consistently lower at high than at low air movements until the dry-bulb temperature was below 83°F and the wet-bulb temperature was below 75 F, when very few men reported sweating.

The second series of observations was made at Singapore on European and Asian men and women. The majority of the Europeans were members of the staff of the Unit and their wives. The Asian men and women, who comprised Chinese, Indians and Malays, were mostly members of the University staff or were employed by the Unit. The technique for recording comfort votes varied a little according to the familiarity of the subjects with the use of a thermometer, but in general they were provided with a supply of 'comfort vote slips', a sling hygrometer and a set of clearly worded instructions. The vote slips again provided a seven-point scale of comfort, and four categories of perceived air movement. In addition, they asked for assessments of the wetness of the skin, at five points on the body, on a three-point scale. The subjects were requested to complete the vote slip and, having done this, to record the wet- and dry-bulb temperatures. They were asked to do so indoors at representative periods throughout the day with the proviso that the votes should not be recorded when the subjects were actually engaged, or had been engaged within the last hour, in strenuous physical exercise. The main findings are summarized in Table 122 and very largely confirm the previous findings for naval ratings. The main conclusion derived was that the comfortable levels of warmth for groups of acclimatized European men and women, and Asian men and women residents, are very similar and are not markedly affected by differences in age, sex or race.

It is important to compare these results with similar findings elsewhere. When they are compared with the results obtained in other parts of the world in which the climate is similar to that in Singapore, it is found that there is general agreement on the zone of temperature preferred. Rao (1952) found that in Calcutta, where winter and summer seasons are more marked, the comfort zone throughout the year lay between effective temperatures of 68°F and 76·5 F, and that the optimum temperature was 72·5 F. In Iran (Grocott, 1948) an effective temperature of 77·5°F was considered to be the upper limit for indoor 'comfort-cooling'. In Sydney (Drysdale, 1950) it was found during hot summer weather that 84 F dry-bulb temperature was the desirable upper limit for calm humid conditions.

These findings are in marked contrast with those found in colder climates. For example, Bedford (1948), in one investigation, found that the preferred zone of temperature in winter in the United Kingdom lay between effective temperatures of 57°F and 63 F. This observation gives point to the necessity for further investigations in other climates, for, until the conditions preferred by those who are to experience them are known, it is impossible to lay down satisfactory standards for either ventilation of warships or the air-conditioning of buildings.

HOT-CLIMATE FATIGUE

The fruitful results of the enquiry into the limits of thermal comfort for men serving in ships in tropical waters led to an enquiry into the occurrence in the Royal Navy of what has been termed 'hot-climate fatigue' or 'tropical fatigue'. Naval officers and ratings serving ashore and afloat in the tropics were furnished with a questionnaire concerning the effect of climate on their efficiency and health.

The results of the analysis of the answers were reported to the Royal Naval Personnel Research Committee (Ellis, 1951*c*) and later published (Ellis, 1952*c*). In summary, it was found that the majority of those serving in ships considered that they were less efficient in the tropics than when serving afloat in more temperate waters, and that two-thirds of those living ashore thought they were less efficient than when serving ashore in England. Climatic factors were considered to be the main cause of this loss of efficiency by about 80 per cent of 182 men who thought they were less efficient, and only 5 men considered domestic, economic or related factors to be more important than climate. The views expressed by officers and men were in close agreement. The analysis of the answers to the questions concerning health showed that whereas about 70 per cent of those in ships thought they were less healthy, nearly the same proportion of those living ashore thought they were at least as healthy in the tropics as in a temperate climate.

In the subtitle of his report ('A Review of Lay Opinion') the author was careful to stress that his findings concerned opinions or beliefs held by laymen, but it is nevertheless this very fact which makes them of importance to all those concerned with the welfare of large groups of people, both civilians and those in the Services, in the tropics. Indeed, the demonstration of the existence of such widely held beliefs is the best indication of the value of climatic physiology and of the need for their substantiation or disproof.

SALT CONCENTRATION OF SWEAT AND ITS RATE OF EVAPORATION

Perhaps the best example of work which was done as the result of an observation made during the course of the systematic experiments at Singapore was the investigation of the role of the salt concentration in the rate of evaporation of sweat. It was reported to the Royal Naval Personnel Research Committee (Lee, Macpherson & Newling, 1952) and the results have been briefly communicated elsewhere (Macpherson & Newling, 1954).

It was observed that in experiments in hot dry climates evaporation of the sweat was often complete and crystals of salt could be seen on the skin (a familiar enough observation in desert conditions), but that in hot moist climates, especially when the air was close to saturation (e.g., dry-bulb 90°F, wet-bulb 88°F), excessive quantities of sweat were produced that dripped wastefully to the floor. It was thought that this failure to evaporate under environmental conditions of high water-vapour pressure might be associated with the depression of the vapour pressure of the sweat by the dissolved sodium chloride. To determine to what extent the rate of evaporation of a solution of common salt might be affected by its concentration, the following simple experiment was performed.

A saturated solution was made by adding sodium chloride to boiling distilled water until no more would dissolve and then allowing it to cool, when some salt crystallized out. From this saturated solution four other solutions were prepared by making 50 ml., 100 ml., 150 ml. and 200 ml. of the saturated solution up to 250 ml. with distilled water. These were called 20, 40, 60 and 80 per cent saturated and, together with distilled water (0 per cent) and the saturated solution (100 per cent), provided six solutions ranging from zero concentration to saturation in equal steps. Each solution was then titrated against a standard silver nitrate solution to determine the chloride content exactly. Forty ml. of each of the six solutions were pipetted into identical chemically clean, weighed, 50 ml. Pyrex beakers. (Equal volumes rather than equal weights of the solutions were used in order to ensure that such factors as the level of the solution below the rim of the beaker, which might be expected to affect the rate of evaporation, would be the same for all.) Each beaker, with its contents, was then weighed and placed in one corner of a hexagonal rack and, to exclude dust, the rack was covered by a fine cheese-cloth screen suspended some distance above the beakers. Exactly 24 hr later each beaker was re-weighed to determine the loss by evaporation.

As the environmental conditions of temperature, humidity and air speed in the room could not be controlled, and as it was possible that the position in the rack might influence the rate of evaporation, the experiment was performed six times on 6 successive days as a 6 × 6 Latin square with days, position and concentration as the variables, thus allowing for the removal, in the subsequent analysis, of any effect due to days or position. In the event, the analysis of the results showed that whereas the effects of concentration and 'days' were highly significant, position in the rack had no significant effect.

The mean temperature during the day-time for the 6 days was dry-bulb 85°F, wet-bulb 79°F, and although the daily average of the dry- and wet-bulb temperatures did not differ by more than 3°F, it is interesting to observe that this produced a significant difference in the amount of water evaporated each day.

The effect of the concentration on the mean daily rate of evaporation is shown in Table 123 and Fig. 39. The interesting points are the linear relation between concentration and rate of evaporation and that the amount lost by the concentrated solution was very small, being of the order of a fortieth of that lost by the distilled water. This would seem to indicate that the concentration of the salt in sweat has a very large effect on its rate of evaporation.

More careful examination of the results will show, however, that the experiment as performed constitutes a special case. It was a chance effect, due to the actual conditions of the experiment, that the loss from the saturated solution should be very close to zero. The following table, based on data given in the International Critical Tables (National Research Council, U.S.A., 1928), sets out the vapour pressure at 85°F of the solutions used.

Saturation of solution (%)	0	20	40	60	80	100
Vapour pressure (mm Hg)	30·8	29·7	28·4	26·8	25·0	23·0

At 85°F (the average day-time temperature of the experiment) the vapour pressure of a saturated solution of sodium chloride is 23 mm Hg, but the vapour pressure of the air at dry-bulb 85°F, wet-bulb 79°F (the average day-time conditions of the experiment) is 23·7 mm Hg, so that, as the rate of evaporation depends on the difference in vapour pressure, a negligible change in weight of

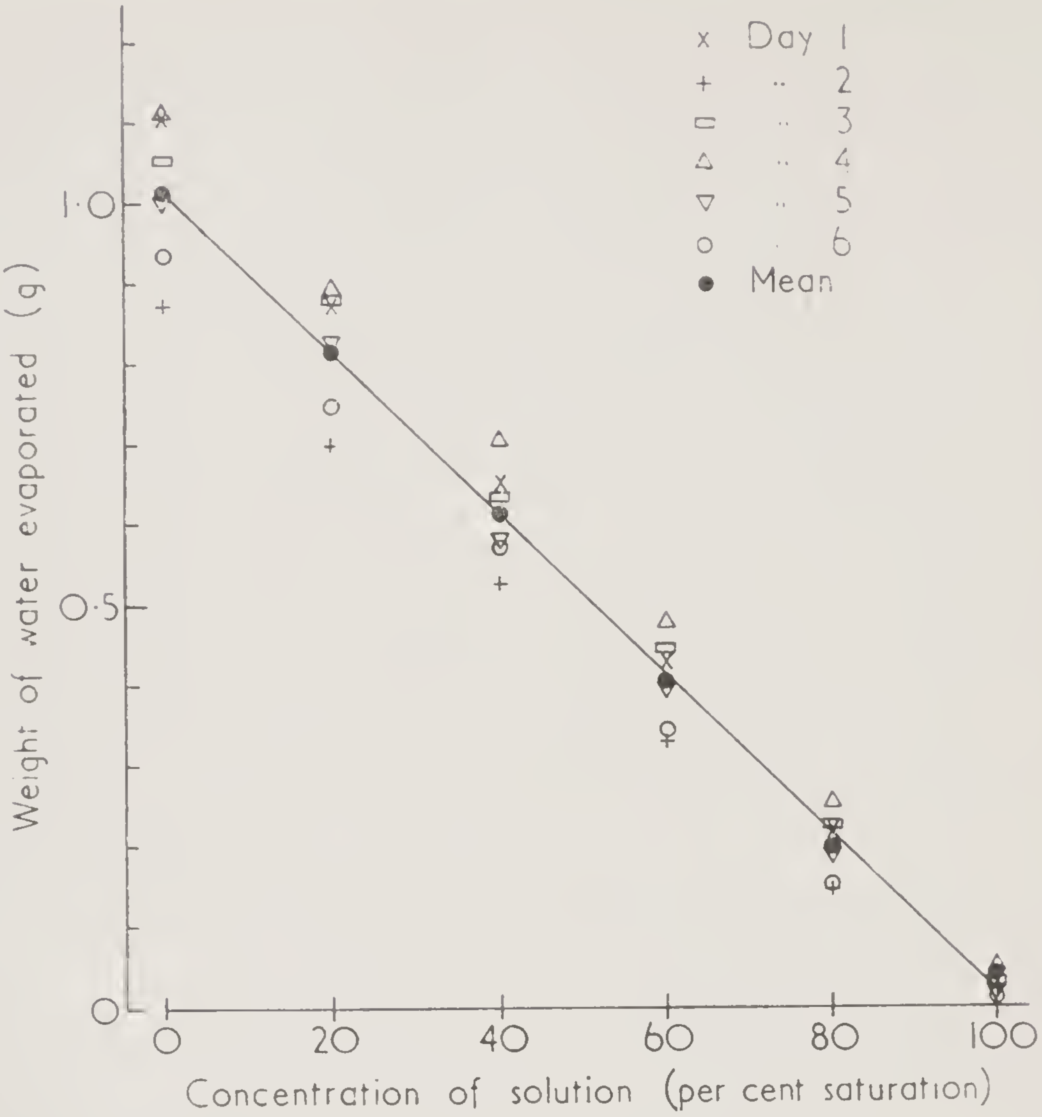

FIG. 39. The relation between the concentration of a solution of sodium chloride and the weight loss by evaporation at room temperature.

the saturated solution is to be expected. If the experiment had been conducted under much drier conditions the loss from the saturated solution would have been much greater. This finding, however, does indicate the true significance of the results from the point of view of evaporation of sweat.

The salt concentration of sweat on the skin can range from 50 mg NaCl per cent in freshly secreted sweat in well acclimatized subjects to saturation with sodium chloride when the sweat is drying on the skin. However, the difference in vapour pressure between distilled water and a saturated solution of salt is small—7·8 mm Hg at 85 F—so that in hot dry atmospheres, when the difference between the environmental vapour pressure and that on the surface of the skin is large, evaporation at a rate sufficient to maintain thermal balance at moderate heat loads takes place irrespective of the concentration of the salt on the skin. Under these conditions, evaporation to dryness occurs and the skin becomes encrusted with salt crystals. In hot moist conditions this does not occur.

For example, consider the case of a naked man working at a constant rate in a hot moist environment with a low air movement (e.g., dry-bulb 90 F, wet-bulb 88 F, air speed 100ft./min, work rate 150 kcal.m^{-2}.hr^{-1}). The skin temperature would be about 95 F, so that, compared with the evaporative heat loss, the radiant and convective heat loss would be small, and could be neglected. The vapour pressure of air at dry-bulb 90° F, wet-bulb 88° F, is 33·5 mm Hg, and the vapour pressure of the sweat on the skin, if freshly secreted and hence of low salt concentration, may be considered to be 42·3 mm Hg (the vapour pressure of water at 95° F), so that the difference between the vapour pressure of the environment and that of the sweat would be only 8·8 mm Hg and within the range in which it would be affected by changes in the concentration of the solutes in the sweat.

Suppose the man achieves thermal equilibrium when his body is completely wet with sweat (a condition necessary for maximum evaporation to occur) and that the rate of evaporation of sweat is exactly equal to the rate of production so that no dripping occurs and the amount of sweat on the body remains constant. Then, as evaporation proceeds the concentration of the sweat will rise, its vapour pressure will fall, and the rate of evaporation—and hence the rate of heat loss—will diminish, and the subject will no longer be in equilibrium with the environment. To restore equilibrium the rate of evaporation must be restored to its original value. This may be done in one of two ways. Either the skin temperature must rise to increase the vapour pressure of the sweat on the skin and thus restore the differential previously existing, or the concentration of the sweat must be restored to its original value.

The permissible rise in skin temperature is limited and any rise is undesirable physiologically. Therefore, the preferable means of adaptation is the second course, the reduction in the concentration of the sweat on the skin. This can only be achieved by secreting sweat at a rate in excess of the rate of evaporation. This in turn will lead to dripping, and permanent equilibrium can be attained only if salt is removed in the dripping sweat at the same rate as it is secreted. If thermal equilibrium is attained before the body is completely wetted, the onset of dripping is delayed until the limits of compensation by increasing the wetted area of the skin are reached and then the same course of events will follow.

The greater the amount of sweat lost by dripping, the more closely the sweat on the body surface will approach the composition of freshly secreted sweat. As the minimum salt concentration is that of freshly secreted sweat, large losses by dripping provide the conditions under which evaporation occurs most readily.

In general terms it may be said that, if the convective heat loss may be neglected, when the vapour pressure of the immediate environment is greater than the vapour pressure on the skin of a saturated solution of sodium chloride (neglecting the other solutes in sweat), loss by dripping will take place whatever may be the rate of heat production. The amount by which the vapour pressure of saturated sweat on the skin must exceed the vapour pressure of the environment before dripping does not occur depends on the rate of heat production by the body.

In the foregoing discussion sweat has been considered, for the sake of simplicity, as a solution of sodium chloride. The argument may, however, be readily applied in a similar fashion to the total solutes in sweat.

This experiment appeared to show, then, that under conditions which are analogous to those of the experiment, namely, when the vapour pressure of the sweat is not greatly different from that of the environment, i.e., in hot moist climates, an increase in the salt concentration in the sweat on the body is likely to affect appreciably the rate of evaporation of the sweat from the skin. Furthermore, the result of the experiment would suggest that the profuse loss of sweat by dripping which occurs under such conditions, far from being merely a wasteful loss of body salt and water which contributes nothing to evaporative cooling, is, on the contrary, a necessary means of physiological adaptation to the environment.

One of the characteristics of acclimatization to heat is said to be a decrease in the concentration of sodium chloride present in the sweat secreted (Dill, Jones, Edwards & Oberg, 1933). This is usually only considered to be a mechanism by which the body conserves salt, but it is clear that another advantage of this decrease in salt concentration is that, if it is not accompanied by a corresponding rise in other solutes, it assists the evaporation of the sweat and consequently the loss of heat from the body.

RACIAL DIFFERENCES IN THE RESPONSE TO HEAT STRESS

In retrospect, it is a matter of regret that on account of the crowded timetable, and for other reasons, it was not found possible to exploit to the full the opportunities offered by Singapore for the examination of the effects of hot environments on members of the several races of indigenous Asian inhabitants. One such investigation was made and, though it was brief and in many ways inconclusive, the results assume a particular importance owing to the paucity of information on the comparative effects of hot environments on members of different races. The findings have been reported in full by Adam, Ellis and Lee (1953).

The purpose of this series of experiments was to study the reactions of six Asians (two Malays, two Chinese and two Southern Indians) to hot environments and to a period of artificial acclimatization, and compare these findings with those for six European naval ratings. The subjects' responses to a hot wet environment (dry-bulb temperature 90°F, wet-bulb temperature 86°F, air speed 50 ft./min) and to a hot dry environment (dry-bulb temperature 120°F, wet-bulb temperature 83°F, air speed 500 ft./min) were measured and they were then acclimatized further by exposure daily for fourteen days, for increasing periods up to 4 hr daily, to a climate of dry-bulb 100°F, wet-bulb 94°F and an air speed of 300 ft./min. At the end of this time they were re-exposed to the climates in which they were first examined.

In the event, only three of the Asian subjects (two Malays and one Indian) completed the whole programme, and the results given are those for these three subjects and for the six Europeans, all of whom completed the programme of experiments.

On the whole, when due allowance is made for differences in physique, nutrition and motivation, the two groups of subjects, European and Asian, behaved similarly, but there were differences of importance, chiefly those concerned with the amount and the composition of the sweat secreted.

The amount of sweat lost by the Asians was always less than that lost by the Europeans in the same conditions—even when allowance was made for the difference in body size. During the two-hour exposure on the first day of the acclimatization process the mean sweat loss of the six European subjects was 26·8 g/kg body weight, whilst that of the three Asian subjects was 16·8 g/kg body weight. The sweat output of both groups increased during the period of acclimatization so that on the thirteenth day the sweat loss during the first two hours of the four-hour exposure was 31·4 g/kg for the Europeans and 21·0 g/kg for the Asians. The difference between the output of the two groups was thus maintained.

There was no great difference in the water intake of the two groups. That of the Europeans rose from 15·5 g/kg for the period in question on the first day of the acclimatization period to 21·1 g/kg on the thirteenth day. In the case of the Asians there was a fall from 20·6 g/kg to 17·6 g/kg. There was thus a much greater disparity between the fluid intake and output for the Europeans than for the Asians, so that the difference in sweat output cannot be explained on the basis of the relative degree of dehydration. Throughout the acclimatization period there was very little difference in the rectal temperature and the pulse rate of the two groups. The inference, therefore, is that the Asian subjects succeeded in adjusting to the stress of the hot environment with a marked economy of water turnover.

Each subject wore an impermeable oiled-silk bag on his left arm from which the sweat was periodically collected for analysis. Weiner and van Heyningen (1952) have shown that sweat collected in this fashion is always more concentrated than that secreted from exposed portions of the body. It is reasonable, however, to use the amount of chloride collected from these bags to compare the amounts of chloride lost in sweat by the two groups. During the period of acclimatization, although the amounts collected from the Europeans varied widely from subject to subject, the mean amount was always much greater than that collected from the Asians. On the first day of the acclimatization period the amount of chloride (calculated as NaCl) collected in the sweat bags of the Europeans was 8·9 mg/kg body weight and in those of the Asians 1·4 mg/kg body weight. On the thirteenth day the amounts were 9·3 mg/kg and 2·5 mg/kg.

In summing up, the authors of the report state—'The evidence suggests that if it were possible to provide men of a similar age with a similar diet and to give them similar work to do in a similar climate for several years, and the groups selected were reasonably representative samples of the races in question, the difference in physiological response to work at high temperatures which could be attributed to racial factors alone would be small'.

BASAL AND RESTING PHYSIOLOGICAL VALUES IN THE TROPICS

Perhaps the best example of work that was the fruit of co-operation between the Department of Physiology of the University of Malaya and the Royal Naval Tropical Research Unit was the determination of basal and resting physiological values in a group of young servicemen in Singapore, carried out conjointly by members of both institutions under the direction of Professor R. Scott MacGregor. The results were reported to the Royal Naval Personnel Research Committee (Adam, John, MacGregor and Yap, 1951).

For more than half a century, in fact, since the work of Eijkmann in the Netherlands East Indies during the closing years of the nineteenth century, there has been a strong division of opinion as to whether residence in tropical areas affects such physiological values as the basal and resting metabolic rate, pulse rate, blood pressure, and the composition of the blood as shown by the number of red and white cells and the amount of haemoglobin present.

Contradictory findings with respect to these matters can be abundantly quoted, and any reading of these will at once suggest that much of the divergence of opinion arises from the differences in the conditions under which the investigations were made and in the techniques employed. Professor MacGregor and his colleagues therefore undertook the determination of these values on a large number of healthy young men under controlled conditions, using carefully standardized methods. The more important of their investigations were made on 103 subjects who had spent, on the average, 18 months in the tropics. They were examined, where appropriate, in the resting and in the basal state. The resting state was defined as that existing after a period of recumbency on a couch in a quiet room. The basal values were determined at 8 a.m. after fasting from 6 p.m. the previous day. The observations were repeated on 4 successive days. In half the cases the subjects slept in the laboratory and were examined before rising; in the remaining half they were conveyed to the laboratory with the minimum of disturbance. There was no significant difference between the results obtained in these two groups.

The values obtained for the pulse rate, systolic blood pressure and diastolic blood pressure were all within the range usually accepted as normal in temperate climates, but within that range the values obtained in the basal state were significantly less than those obtained in the resting conditions. (Resting values: pulse rate 66·6 beats/min, blood pressure 123·4/75·7 mm Hg. Basal values: first day, pulse rate 56·7 beats/min, blood pressure 115/73 mm Hg; fourth day, pulse rate 56·0 beats/min, blood pressure 109·7/69 mm Hg.)

The values obtained for the mean basal metabolic rate (first day, $38{\cdot}41 \pm 0{\cdot}472$ kcal.m^{-2}.hr^{-1}; fourth day, $36{\cdot}09 \pm 0{\cdot}486$ kcal.m^{-2}.hr^{-1}) were also within the range of values found in temperate climates, but it is to be noted that the values found on the fourth occasion were significantly lower than those found on the first.

The haematological values—red cell count, haemoglobin content, haematocrit, volume index, mean corpuscular haemoglobin concentration, mean cell volume and the total and differential white cell count—were all within the normal ranges.

The conclusion was drawn, therefore, that residence in the humid tropics on the average has no effect on these physiological values. This does not mean that the values for some individuals may not be affected; rather it means that since these effects are likely to be small, measurements made with the greatest care and the most exact techniques will be required for their unequivocal demonstration.

THE VITAMIN CONTENT OF SWEAT

The last of the ancillary studies was provoked, only a few days before the climatic chambers were dismantled, by a suggestion that, with such large sweat losses as some of the subjects and many men in warships experienced, there might be also significant losses of water soluble vitamins calling for the appropriate dietary supplements. It was fortunate that Professor J. W. H. Lugg of the Biochemistry Department of the University of Malaya was able to set up at short notice the necessary apparatus for estimating ascorbic acid and thiamine in sweat and urine and for evaluating the effect of supplementing the ascorbic acid intake for subjects acclimatized to Singapore who were working in climates rather warmer than the normal Singapore climate.

It was concluded (Lugg and Ellis, 1954) that it was unnecessary 'to supplement the ascorbic acid or thiamine intakes of European men working in warm environments in the tropics to offset such losses as occur in the sweat, provided they are already receiving normal amounts of these vitamins in their daily diet'.

ACCIDENTAL OBSERVATIONS

Some of the most significant scientific discoveries have been made as the result of chance occurrences observed during the course of experiments directed to other ends. It was perhaps inevitable that in the large number of experiments conducted at Singapore opportunities would arise for the making of observations of the effects of warm environments that were quite unrelated to the main purposes of the experiments—indeed, it might be said that every case of heat incapacitation provided such an opportunity; however, there were also chance happenings, quite unforeseen, which, though they in no sense led to important discoveries, did provide useful information of some interest. Three such may be quoted.

Miliaria Profunda

The first was the occurrence of a case of generalized miliaria profunda among the subjects used in the experiments on heat incapacitation. This provided the opportunity for the study of the disease under controlled experimental conditions. Observations were made on the effect of the condition on the subject's pulse rate, body temperature and sweat loss, and his ability to withstand hot environments, with an exactitude that in other circumstances would not have been possible. The results were reported to the Royal Naval Personnel Research Committee (Ellis, Hare & Lind, 1954) and subsequently published (Ellis, Hare & Lind, 1955).

Temperature Regulation in the Febrile

A second example of some interest was afforded by the occurrence of a febrile illness (upper respiratory tract infection) in a subject during the course of the series of experiments on the effects of radiant heat. It happened by chance that he was one of three subjects who were particularly well matched, in that their reactions to heat were so similar that given the findings on any two the values for the third could be predicted with some confidence.

This man volunteered to continue as a subject during his illness, so that it was possible to compare his results when febrile with the results of the other two subjects—which could be taken to represent his reactions in the same circumstances when afebrile. It was found that, as his illness progressed and his body temperature rose, his skin and rectal temperatures behaved during the experiments exactly as would have been expected had he been afebrile, in that they rose and fell by the expected amounts; but in each experiment they exceeded the values that would have been expected by the amount by which his body temperature was above normal before the experiment began. In other words, the subject regulated his temperature exactly as he would have done if he had been afebrile but about a new, higher level. To put it in unscientific language, it appeared that the effect of fever was to turn up a notch at a time, as the severity of the fever increased, the level at which the body thermostat was set and to turn it down again as defervescence ensued.

A further point was that the subject's sweat losses during the course of the experiment were those which would have been expected if he had been afebrile. The implications of this are important; while at first sight the finding may appear somewhat surprising, it is clearly what would be expected if the sweat loss is adjusted to meet the needs of the heat exchange of the body. An account of these findings has been published (Macpherson, 1959).

The Experimental Significance of the Diurnal Variation in Body Temperature

Yet another chance observation with important implications arose from work, done under the direction of Major J. M. Adam and later briefly described in a communication to the Physiological Society (Adam & Ferres, 1954), on the diurnal variation in body temperature. In these investigations, which were later continued at Oxford, the oral and rectal temperatures of a number of men were recorded under carefully standardized conditions throughout the day. At Singapore two series of such measurements were made—a preliminary series in which the oral and rectal temperatures were recorded at six specified times daily for 8 days on fourteen subjects, and a definitive one in which the oral and rectal temperatures were recorded from 6.30 a.m. to 10 p.m. at half-hourly intervals on seven subjects over periods of from 2 to 7 days.

That there is a diurnal variation in the body temperature has been known for more than a century (Davy, 1839, 1845, 1850; Ogle, 1866; Casey, 1873; Ringer & Stuart, 1877), but Adam and Ferres were able to show, when they compared the results for Oxford and Singapore, that although the shape of the curves representing the diurnal rhythm was very similar for the two places, the rectal temperature was, on the average, 0·43°F higher and the oral temperature 0·35°F higher in Singapore than in Oxford. Furthermore, they were able to show that the changes from 6.30 a.m. to 10 p.m., as observed in their second series, could be expressed in the form of an equation so that, given the time of day, the oral or rectal temperature of men seated at rest either in Oxford or Singapore could be predicted with accuracy.

In Series III (Chapter 4), half the experiments had been performed in the morning and half in the afternoon. Each morning experiment, beginning at 9.0 a.m., was duplicated in an afternoon experiment, beginning at 1.0 p.m. When the results of the duplicate experiments were examined, it was observed that the rectal temperature of the subjects on entering the climatic chamber at 1.0 p.m. was, on the average, 0·53°F higher than the corresponding value at 9.0 a.m. When, however, the temperatures were compared after the third work period, 2 hr and 40 min later, i.e., at 11.40 a.m. and 3.40 p.m., the difference was reduced to 0·21°F for the experiments at 90°F, 0·28°F for the experiments at 100°F and 0·10°F for the experiments at 120°F.

The equation proposed by Adam and Ferres to relate the time of day to the rectal temperature for young men seated at rest in Singapore was

$$Y = 98{\cdot}315 + 0{\cdot}12512x - 0{\cdot}00309x^2$$

where y is the rectal temperature and x the time in half hours after 6.30 a.m. From this equation, which is represented by the curve in Fig. 40, the following values can be calculated.

	Time	*Rectal temperature* (°F)	*Time*	*Rectal temperature* (°F)
Morning	0900	98·86	1140	99·28
Afternoon	1300	99·42	1540	99·57
Difference		0·56		0·29

If these values are compared with those obtained in the duplicate morning and afternoon experiments in Singapore, it will be seen that the observed difference between the rectal temperature on entry at 9.0 a.m. and at 1.0 p.m. of 0·53°F is in good agreement with the value (0·56°F) predicted by the equation.

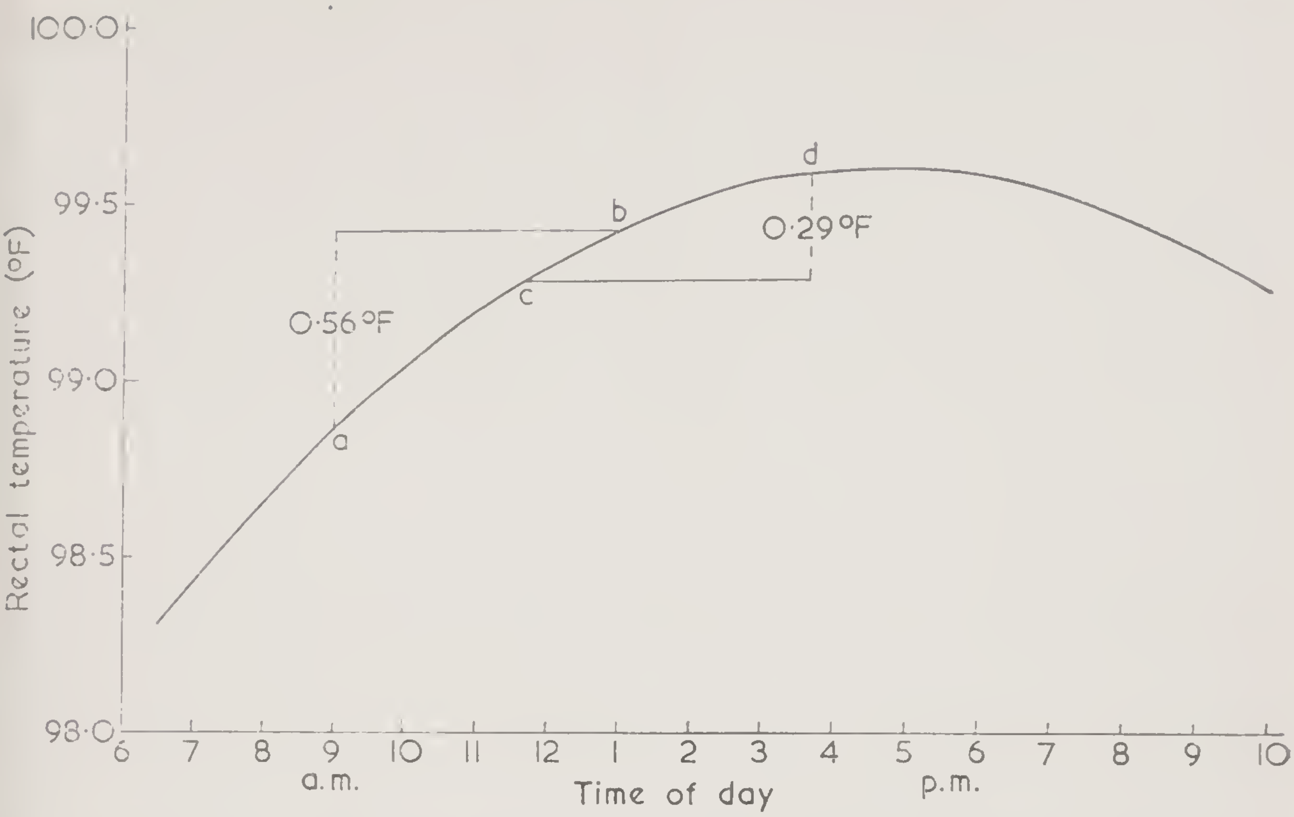

FIG. 40. The relation of rectal temperature to time of day for young men resting seated at Singapore. Differences between 9 a.m. and 1 p.m. and between 11.40 a.m. and 3.40 p.m. (times of beginning morning and afternoon experiments and of ending morning and afternoon third work periods) are indicated.

If, during the experiments, the men had remained seated at rest for the ensuing 2 hr and 40 min in the ordinary Singapore environment, the difference between the rectal temperatures would have diminished to 0·29°F as the result of the normal cyclic diurnal change. The subjects were, in fact, exposed to a wide range of environmental conditions and worked at two very different rates of energy expenditure. Nevertheless, the differences between the morning and afternoon experimental groups diminished in a manner which is very comparable with that for men at rest outside the climatic chamber.

The observed differences in experiments at 90°F (0·21°F) and at 100°F (0·28°F) were in very satisfactory agreement with that predicted, but the difference in experiments at 120°F (0·1°F) was less so. It is thought, however, that owing to the large variations in rectal temperature in these men when approaching exhaustion, as they very often were at 120°F, the last agreement is as good as could be expected.

It would appear, therefore, that any increment in the deep-body temperature resulting from environmental stress or expenditure of energy is additive not to a fixed but to a varying basal level determined by, among other factors, the time of day.

As a corollary of these findings it may be concluded that the diurnal rhythm in body temperature is not the result of variation in the environmental temperature throughout the day.

It has been pointed out (Macpherson, 1957) that these conclusions have an important bearing on the interpretation of the results of experiments on the reactions of man to environmental stress. If, for example, an experiment was performed in which a group of men sat at rest in the environment of Singapore for 2 hr 40 min on two occasions, once in the morning and once in the afternoon, their rectal temperatures would correspond with the calculated values quoted on p. 198. If the height of the final rectal temperature was considered to provide a suitable criterion of physiological strain it would be concluded either that the environment in the afternoon was more severe or that the men were less acclimatized on this occasion. If the increment in rectal temperature was used as the criterion, contrary conclusions would be drawn. None of the conclusions, however, would necessarily be correct. The implication is that when either the final rectal temperature or the increment in the rectal temperature of two groups of subjects is being compared, erroneous conclusions as to the relative stress of the environment or the degree of acclimatization of the subjects may be reached if allowance is not made for the diurnal variations in body temperature.

SUMMARY

1. An account is given in this chapter of a number of investigations made at Singapore which lay outside the main stream of the work described in the previous chapters. Some were *ad hoc* enquiries concerned with naval or army problems, some additional investigations arising out of the main body of work, some were conducted in association with the University of Malaya, and some arose from accidental observations in the course of other experiments. The more important are briefly described.

2. *The physiological effects of wearing jungle uniforms.* It was not found possible to distinguish on physiological grounds between different types of uniforms which in the view of both observers and subjects differed as to their suitability for use in the tropics. Attention is drawn to the importance of physical tests of materials and to the role of such matters as texture, weight and absorbency of garments in determining the comfort of clothing.

3. *The measurement of radiant heat.* Measurements of mean radiant temperature and the amount of heat gained by a man at various levels of mean radiant temperature were made by means of metal model men, one black and one polished, specially designed for this purpose. These experiments confirmed the validity of the globe-thermometer as a measure of mean radiant temperature and showed that in a non-uniform environment the arithmetical mean of the mean radiant temperatures measured by three globe-thermometers suspended vertically above one another at heights of 2 ft., 3 ft. 9 in., and 5 ft. 6 in. from the floor provided a close approximation to the value of the mean radiant temperature as measured by the metal model men.

4. *Thermal comfort.* A survey by means of 'comfort votes' among a ship's company serving in tropical waters established that discomfort in the heat was closely associated with the onset of sweating. The survey also suggested that an effective temperature of 78° F might be chosen as the upper acceptable level of warmth, as below that value less than 20 per cent of those observed were wet with sweat. A comparable survey among Europeans and Asians of both sexes in Singapore gave results in general agreement with those described.

5. *Hot-climate fatigue.* An enquiry by questionnaire among naval officers and ratings serving ashore and afloat in the tropics revealed that the majority of those questioned considered they were less efficient in the tropics than in temperate climates and, in general, attributed this effect to the climate.

6. *Salt concentration of sweat and its rate of evaporation.* A study of the rate of evaporation of sodium chloride solutions of varying concentrations

demonstrated that the fall in water vapour pressure is sufficient, as saturation is approached, to reduce significantly the rate of evaporation in hot warm atmospheres. Hence it is suggested that the dripping of sweat which occurs in such atmospheres, by preventing any great increase in the salt content, is a means for securing adequate evaporation of the sweat.

7. *Racial differences in the response to heat stress.* A comparison of the physiological reactions of Asian and European subjects to hot environments showed little difference in the behaviour of the two groups except that, even when allowance was made for the difference in body weight, the Asians always secreted less sweat and the amount of chloride collected in their arm sweat-bags was less.

8. *Basal and resting physiological values in the tropics.* This enquiry conducted jointly with the Physiology Department of the University of Malaya established that the resting and basal metabolic rate, blood pressure, pulse rate and the values for the formed elements of the blood in young male Europeans who had lived not less than 6 months and not more than 3 years in the tropics fell within the usually accepted ranges for these values in temperate climates.

9. *The vitamin content of sweat.* A determination of the ascorbic acid and thiamine content of sweat showed that it is unnecessary to supplement the intake of these vitamins by European men working in warm climates in order to offset such losses as occur in the sweat, provided they are present in normal amounts in the daily diet.

10. *Accidental observations.* Some observations of importance made by chance are recorded. The occurrence of a case of miliaria profunda in a subject provided the opportunity to study the natural history of the disease. The behaviour of the rectal temperature in a subject who continued to participate in the experiments while suffering from a mild fever showed that during fever the body continues to regulate its temperature as usual but about a new higher level. Another observation showed that the base line from which divergence of the deep-body temperature occurs during heat stress is determined by the diurnal variation in body temperature.

CHAPTER 10. CONCLUSIONS

The work done at the National Hospital, London, and at Singapore was directed towards providing information which was required for specific purposes, and it is therefore pertinent to enquire to what extent these requirements were fulfilled.

The Assessment of Environmental Heat Stress

All the work on the assessment of the stress of hot environments followed, in a logical progression, from the original decision in 1944 that a scale of environmental stress should be chosen and that an acceptable environment in ships should be defined in terms of that scale.

It was logical for the Habitability Subcommittee to choose an existing and much-used scale—the Effective Temperature Scale—and to choose, having given due consideration to the information then available, such a value as 80°F, with a tolerance of 6°F, as the desirable upper limit. This having been done, the workers at the National Hospital undertook the necessary examination of the validity of the Effective Temperature Scale and the determination of whether the value selected as the limit was indeed well chosen.

In the course of their investigations they decided that the Effective Temperature Scale was unsatisfactory in certain respects, and this led to the devising of a new scale (the Predicted Four-hour Sweat Rate) considered to be more suitable, and to the defining of the acceptable upper limit for environmental heat stress in terms of the new scale. Very properly, they re-emphasized the view held by the Subcommittee that in view of the possible difference between the degree of tolerance to hot environments (acclimatization) of their highly trained subjects and that of men actually serving in ships, it was necessary that their conclusions should be checked by examination of men in the tropics. This, then, became the task of the Unit at Singapore.

The Unit was required, in effect, to perform two main tasks. The first was to examine with the utmost care the effects of variations in the several components of environmental stress—air temperature, mean radiant temperature, humidity, air speed, rate of energy expenditure and amount of clothing worn—and to relate these effects to the degree of acclimatization of the subjects.

The examination in great detail of the effect of variations in environmental stress was essential for a number of reasons. It was necessary to confirm the criticisms made of the Effective Temperature Scale, but it was also necessary to examine the proposed new scale, the P4SR Nomogram, equally critically. The nomogram had been based on certain environmental conditions used in London and on the resulting sweat losses observed. If these environmental conditions are substituted in the nomogram, it necessarily reproduces the observed sweat losses—within the limits of sampling error—provided its construction is correct. As it seemed to satisfy this test (McArdle *et al.*, 1947), there was a *prima facie* case for its use in environmental conditions similar to those on which it had been based. Whether it could be so used was one of the questions to be answered at Singapore.

Attention had to be given to the effects of all the environmental factors, but the effects of one, the mean radiant temperature, had to be examined with special care. Compared with the amount of work done on the physiological effects of variations in temperature, humidity and air speed, little had been done on the effects of increasing the mean radiant temperature above the air temperature, largely because, or so it would appear, of the difficulty of providing suitable apparatus. The facilities at the National Hospital for the study of radiant heat had been by no means satisfactory, and only a small number of observations on the effects of this factor had been possible. It was necessary, therefore, to devote special attention to the subject at Singapore.

All these investigations, and the associated experiments to which they gave rise, had to be conducted with the second main task of the Unit in mind; this was the study of the effects of acclimatization in relation to the problem of the acceptable levels of warmth in ships. From many points of view, theoretical as well as practical, this was one of the chief interests of the work at Singapore.

The conclusions reached concerning the physiological effects of the several environmental factors have been set out at length in previous chapters, and need be summarized here only in the briefest fashion.

The demonstration by the workers at the National Hospital of the disproportionately deleterious effect of low air speeds in very humid environments was amply substantiated; so also was the change from an initial beneficial effect of increasing air speed to an injurious one as the air speed increased further, especially for men lightly clad in a hot dry climate. As a corollary it was shown that the criticisms made of the Effective Temperature Scale on the ground of its failure to indicate correctly the effects of air speed were well founded. On the other hand, the statement of the London workers that the Effective Temperature Scale over-emphasizes the effect of the wet-bulb temperature and under-emphasizes the effect of the dry-bulb temperature was not confirmed. Moreover, the experiments on the effects of added radiant heat at Singapore, contrary to the views expressed at the National Hospital, supported the validity of the 'correction' of the Effective Temperature Scale proposed by Bedford in order to enable the Effective Temperature Scale to include the effect of the mean radiant temperature in its assessment of environmental stress. The examination of the effects of the various environmental factors showed that, in general, the P4SR Index predicts with remarkable accuracy the sweat losses of highly acclimatized, healthy young men when examined in the manner described. In addition, it was shown that the sweat loss is predicted as well in conditions in which the mean radiant temperature is above air temperature as in conditions in which air temperature and mean radiant temperature are the same.

There were, however, occasions on which the sweat loss observed did not agree with the sweat loss predicted by the P4SR Nomogram, and this raises the question of whether the Nomogram is in error in its prediction and whether it should therefore be corrected. This is an important question, and one that must be considered with the utmost care. In as much as the P4SR is a function of the environment it is a measure of environmental stress rather than one of physiological strain. There is no upper limit to the environmental stress which can be imposed, but there is a limit to the amount of sweat which can be secreted, and, furthermore, the amount of sweat secreted in a given environment will vary from person to person. Both these points were fully appreciated by those who devised the P4SR, and it was found necessary, in order that the P4SR should provide an accurate measure of environmental stress, that it should be permitted to diverge from the values of the sweat losses as determined experimentally. This substitution for the observed sweat loss of a conventionalized sweat loss has, as pointed out on p. 307, much to recommend it, but it has this far-reaching implication—it makes impossible the verification of the P4SR

Index in all cases by the simple expedient of measuring the sweat loss of fit acclimatized young men.

It is appropriate to raise in this connection the question of the dimensions of the P4SR Index. This index is not a rate, but an amount. It is expressed as a volume, whereas it represents a conventional weight loss. For these reasons it is suggested that the value for the environmental stress which it represents should be expressed as a dimensionless index, so that 'Predicted Four-hour Sweat Rate 3·5 litres' becomes 'P4SR Index 3·5'.

The demonstration of anomalies in the Effective Temperature Scale likewise raises the question of whether an attempt should be made to remove them. If the scale is in error in the effects which it ascribes to changes in air speed, should it not then be put right? This could be done. Indeed, it has been shown (Smith, 1952) that the scale can be modified to include the effect of more than one level of energy expenditure; thus one of the criticisms of this scale (Appendix, p. 295) has been met. There is also no serious obstacle (except the growing complexity) in the way of adapting this scale to include the effects of more than two levels of clothing. Whether the accomplishment of this desirable end would be worth the enormous amount of labour involved is another matter. It is perhaps wiser to accept the scale for what it is, a convenient method of assessing comfort (or discomfort) in the middle range of environmental stress, in which it has demonstrated its value for more than 30 years, and not to attempt to apply it outside this range. Such pitfalls in its use as those mentioned in Chapter 8 (p. 170), which derive from the anomalies originally observed by the London workers (Appendix, p. 286), will then be avoided.

A single index of the integrated effect of all the factors which contribute to environmental stress is so clearly desirable that much effort has been expended in the search for it. The usual method of approach has been to select one or more of the measures of physiological strain (even 'comfort' which can only be subjectively appreciated is such a measure) and to compare the effects of a series of environments on the selected measure. In effect, it is assumed that the physiological strain produced is a measure of the environmental stress applied. The difficulty has always been to select a suitable measure of physiological strain. The conclusion reached in the present series of investigations would seem to be that over the range of heat stress in which sweating occurs, or rather over the lower end of that range, the amount of sweat secreted provides the best single measure of physiological strain and thus of environmental stress. (It was not possible, however, to provide any formal proof that this was so.) It would seem, therefore, that the P4SR Nomogram is to be preferred to other scales of a like nature, but it should be noted that, admirable though it is for the conditions for which it was devised, i.e., for an indoor climate with a restricted range of stress, it becomes difficult to apply to conditions which are markedly different, e.g., the external environment in tropical climates.

Methods in which the level of environmental stress is assessed in terms of the degree of physiological strain have one serious defect in common; this arises from the wide variation that exists between individuals in their response to the application of an identical stress. Much of this variation is dependent upon the degree of acclimatization, but even when this source of variation is removed, as the experiments described amply demonstrate, there still remains a substantial variation in response from person to person. If human reactions are used as a measure, however carefully the process of standardization is performed and however strictly the subjects are defined, some degree of residual variation persists. For this reason it would appear preferable to define the environmental stress in terms of a physical measure of components of the environment.

Such a measure is provided by the wet-bulb temperature, one of the earliest single measures of environmental stress to be proposed, and one which is still in use. It combines in a single index a measure of both air temperature and humidity, and to the extent that a sweating human body resembles the wet-bulb of a thermometer it does provide a measure of the stress. Although it fails to provide a measure of other environmental factors it is of considerable value in certain circumstances, for example when the body is completely wetted with sweat, the air speed is relatively low, the difference between the air and skin temperature is not great, and the mean radiant temperature is not far removed from skin temperature. In such circumstances the two important terms in the equation representing heat balance are the rate of working and the rate of evaporative cooling—convective and radiant exchanges are small. It was precisely under these conditions in hot wet mines in Cornwall that the use of the wet-bulb temperature was originally proposed (Haldane, 1905). The wet katathermometer is an improvement on the wet-bulb thermometer only in as much as it includes the effect of air speed.

The best evidence for the need for a single index of environmental stress is provided by the industry with which it has been sought. The convenience of such an index is unquestionable, but there are grave doubts as to whether it is attainable. There are two parts to environmental stress, that provided by the environment and that provided by the subject in the environment. Of these, the part provided by the environment is the more precisely measurable and the simpler. The part provided by the subject comprises, as is clearly shown in Chapter 8, not only the metabolic heat production and the amount of clothing worn, but also other factors such as the rate of replacement of salt and water. Doubtless still more will be identified, although the inclusion of all such factors in a single index would be well-nigh impossible.

The survival experiments described in Chapter 8 drew attention to another complicating factor in the effect of heat stress—the length of exposure. The ability to maintain equilibrium for a short period does not necessarily imply the ability to maintain it for longer periods. Fatigue of the mechanisms of adaptation can occur and exposure to environments which are tolerable for short periods may result in failure to survive them when the exposure is prolonged or repeated. The time before such failure occurs is variable, and depends on the level of the stress imposed and the length of intervening recovery periods. 'Tropical fatigue' could be explained in terms of prolonged exposure without relief to a low level of heat stress.

It is possible, as Winslow, Herrington and Gagge showed more than 20 years ago (Winslow *et al.* 1936*a*, *b*), to estimate the amount of heat gained or lost by a man in a given environment from a knowledge of the air temperature, mean radiant temperature and air speed, provided the skin temperature of the man is known. From this, and the amount of heat produced by metabolism, it is possible to calculate, in the case of hot environments in which sweating occurs, the amount of sweat which must be secreted in order to maintain thermal balance. If the amount required is beyond the capacity of the man to produce or to evaporate with an acceptable skin temperature (which depends upon the vapour pressure of the environment) then the conditions in question will be intolerable.

The application of these ideas by Haines and Hatch (1952) to provide a measure of environmental stress has been examined in Chapter 7, where it is shown that great advantages accrue from being able to express the effect of the environment in terms of the heat exchange. The great benefit of this method is that it provides a rational basis for measuring the effect of the several factors. This approach is far removed from the empiricism of the statement that the wet-bulb is more important than the dry-bulb and it reduces the whole matter to the realistic viewpoint of heat transfer. If, as pointed out in Chapter 7, it was possible to determine the skin temperature with greater accuracy, the actual heat transfer could be calculated even more accurately, although, as the results given in Chapter 6 (p. 118) show, the estimate of 95°F, the assumed value, is not grossly inaccurate in conditions which are likely to apply. Using this approach we can provide a measure of the environmental stress but not a measure of the physiological strain; that can only be determined by experiment.

It would appear, then, that there is no single index which is universally applicable. The Effective Temperature Scale is of greatest value in the middle range of environmental stress—the range of comfort and discomfort—within doors. The P4SR Nomogram is clearly not applicable under conditions in which there is no sweating, but for a range of conditions in an indoor environment it provides a ready means of comparing two sets of environment. Many other scales of stress have been proposed and many more will be devised in the future to meet special conditions, such as the intense heat of furnace fires, very deep mines, supersonic flight, or the cold of polar regions or inter-stellar space.

Such matters touch the work that was done only remotely, but a problem which impinges closely on the work that has been described is that of the measurement of heat stress out of doors. This is mentioned because while the experiments were being conducted in Singapore, and afterwards, there were numerous approaches to the members of the staff of the Unit by those who sought to use the P4SR Nomogram, or some other measure, to assess the stress of outdoor tropical climates. In the tropics, as distinct from temperate climates, hot conditions occur out of doors and in such conditions the radiant heat from the sun contributes a very large proportion of the total heat load. This is commonly recognised but, despite the work of Vernon (1933), Blum (1945), Richards, Stoll and Hardy (1951) and others to develop suitable instruments for the measuring of this component, there exists as yet no simple method by which it may be computed. The problem is a difficult one, complicated by the changing altitude of the sun and the changing profiles of those exposed to it, and by the level of re-radiation from the immediate environment. The solution of this problem is one of the most urgent requirements of applied climatic physiology.

The Desirable Upper Limits of Warmth

Some care was taken in Chapter 1 to explain the significance of the terms 'upper tolerable level' and 'desirable upper limit' as at first conceived, and it has been observed at the beginning of this chapter that it was logical, in the circumstances, to choose some value on the Effective Temperature Scale for the latter. However, all the experience in Singapore served to show how difficult it was in practice to define any such limit.

As at first conceived, 'desirable upper limit' was a relatively simple concept. It was required to determine what environmental conditions could be permitted to exist in the magazines of ships without seriously affecting the ability of the men working there to perform a task requiring a given rate of work for a period of four hours. This is a simple concept of one form of 'toleration'—the ability, under urgent compulsion, to endure a hostile environment for a given period without a serious loss of efficiency.

Such information is important. It has its application not only to the conditions of warfare but also to the crises of civilian life. It is important to know that fit healthy young men, when required to do so, can, for a stated period, continue to perform a given physical task if the environmental stress is not permitted to rise above a certain level. But even such a homogeneous group as fit young naval ratings vary greatly in their ability to withstand heat, and this introduces one difficulty in determining this level. A further difficulty is introduced by the question of the acclimatization of the men concerned. These facts were appreciated by the workers at the National Hospital; hence the caution with which they expressed their opinion as to the desirable upper limit of warmth in terms of the P4SR Nomogram.

When the matter was later investigated at Singapore, the variation in the ability of individuals to withstand heat again became apparent, but what was even more important was the demonstration (Chapter 8) of how efficiency in performing even the simplest tasks may decline before the onset of physical incapacitation.

The possibility of this was recognised by the Habituality Subcommittee when the original investigations were planned, and was indeed the reason why the studies of the effect of environmental temperature on efficiency were undertaken at Cambridge (Mackworth, 1950) and continued later at Singapore (Pepler, 1953-4). This work also demonstrated that efficiency declines with increasing environmental stress; moreover it showed that this decline can be indicated by appropriate tests before the onset of the dramatic loss of capacity observed in the physiological tests of survival. The more refined measures of performance used in the psychological tests revealed further complexities in the ability of men to perform a given task in the heat which were related to other characteristics than physical capacity. It was found, e.g., that to produce a measurable decline in efficiency in receiving Morse signals, a greater increase in environmental stress was required for highly skilled wireless telegraphists than for those less skilled.

At Singapore, information was also obtained on the ultimate limits of tolerance for heat—the conditions in which physical survival is impossible. These are limits which are fairly easily determined. If a man 'collapses', i.e., if he faints or becomes too ill to do further work, that then prescribes a definite end-point for him. As the information was collected, it became apparent that for this limit, too, there were wide individual differences, even in the homogeneous group of young men examined. This became evident in the course of the early experiments when some men survived the four-hour experiments while others were compelled to abandon them. It was, however, most strikingly demonstrated in the systematic examination of the problem in Series IX (Chapter 8). For each individual, the most important factor was his degree of acclimatization to heat. By repeated exposure to hot conditions his tolerance could be improved; indeed this improvement in performance could not be prevented.

Two standards of tolerance can thus be recognised—the 'efficiency limit' and the 'survival limit'. 'Survival' limits, distinguishing as they may between life and death, are important in the crises of war. For most purposes, however, the 'efficiency' limits are more important. For example, although the hand steering position in a ship may be manned only in an emergency, acceptable environmental conditions must be maintained in the compartment; otherwise, when the need to man it does arise the whole purpose of having such an emergency position may be defeated. The survival of its occupants will be pointless if their efficiency is so low that it imperils the safety of the ship as a whole.

The expression 'withstand the environment' implies resistance to a stress and also suggests the importance of the duration of the exposure to the stress. If an environment is withstood for four hours this does not imply that it will be withstood for longer, and repeated application of a stress may be more harmful than a single exposure. The factor of time is particularly relevant, however, in considering yet another limit which, for want of a better word, may be called the 'affective' limit (from 'affect' meaning 'feeling'). Environmental conditions may at first sight and in the short term have no effect on efficiency and yet be unpleasant to work in. It can safely be assumed that the telegraphists used as experimental subjects, if given the chance, would have preferred a much lower environmental temperature than that at which their efficiency began to show a measurable decline. Moreover, continuous exposure to mild degrees of heat stress will in time become, if not intolerable, ill tolerated.

This point is well illustrated in the enquiry by Ellis (1951*c*, 1952*c*) on the incidence of tropical fatigue in men in ships in the Far East, which serves to establish in a service context and in the tropics what has been known for civilians in temperate climates for many years. Vernon (1919) showed that there was a distinct seasonal variation in the output of men working in tin-plate factories. As the weather grew warmer their output decreased. In factories where ventilation was good, seasonal variations were less than in those in which ventilation and, consequently, the environmental conditions, were poor. The number of accidents and severe cuts experienced by the men in three munition factories was shown by Osborne and Vernon (1922) to rise steeply when temperatures rose above 72°F. Absenteeism has been related to environmental temperatures by Bedford (1928). In coal mines where the dry-bulb temperature was less than 70°F, 3 per cent of shifts were lost from sickness. In pits in which the temperature was 75°F to 80°F, absenteeism was higher by 50 per cent. In the large group of men working in mines at a temperature of 80 F and over, the absenteeism was 63 per cent greater than in pits with the lowest air temperature. Bedford and Vernon (1931) were able to confirm these findings and to show that at high air temperatures the number of accidents at the coal face was greater than at low air temperatures.

These findings illustrate the effect of environmental stress of low intensity applied for a lengthy period. In these conditions, the acceptable level of warmth is not at the limit of physical tolerance or where efficiency can be maintained for short periods but where comfort is experienced. It becomes necessary to know the zone of comfort for the persons concerned and this can only be discovered by enquiry. The investigations by Ellis (1953*b*) into thermal comfort zones were thus extremely relevant to the general purpose of the work at Singapore.

There is, then, no short answer to the question of the desirable upper limits of warmth and the environmental conditions that ship constructors should aim to achieve. A separate standard may have to be applied to each compartment: heed must be given to the length of time that men occupy each compartment and to the occupation in which they are engaged. In living spaces such as mess decks the standard to be applied is clearly that of comfort, and in this connection the relation of the onset of sweating to the onset of discomfort must be borne in mind. (The finding by Ellis (1953*c*) that an effective temperature of 78°F rather than 80°F is desirable on mess decks should be noted. The difference, though small, is important because of its relation to the onset of sweating in men at rest.) In those spaces in which men work for long periods of time the standard must likewise be that of comfort. In some situations the achievement of comfort may be a physical impossibility, and the limits set will have to be determined by the effect of the environment on the efficiency of those working in them. It is difficult to imagine any situation in which the acceptable conditions are those which approach the limit of physical tolerability.

It is appropriate to refer here to a criterion of tolerability to which some attention was given during those experiments in which skin temperature was measured, that is from Series IV onwards. The alternation of periods of rest and work in the 'Queen Square Routine' produced a characteristic pattern of response in the skin temperature. At the lowest levels of stress, the skin temperature fell with work and rose with rest, and showed a general tendency to drift downwards throughout the course of the experiment. At the higher levels of stress, the form of the curve was inverted. The temperature rose with work and fell with rest and there was a tendency for the general level of temperature to rise. There was a transition point, which varied somewhat from subject to subject, at which the first type of response gave place to the second, and this presumably represented for the subject the boundary between conditions to which he adjusted without difficulty and those which he found trying. It is perhaps not without significance that if Fig. 12 (p. 83) is examined it will be seen that the Singapore subjects gave the first type of response to the environmental conditions used in the uniformity trials in their series of experiments, and the Oxford subjects the second type of response. It may be concluded, therefore, that the Oxford subjects found the conditions much more severe than did the Singapore subjects. This observation suggests that this change in the skin temperature response might be used as a criterion of the tolerability of an environment for any particular individual.

To sum up, a knowledge of the physically tolerable levels of warmth is important, and equally so is a knowledge of the levels at which efficiency is likely to decline in the length of an ordinary working period; however it is more important to know, particularly for living quarters, the levels at which thermal comfort is experienced.

The Phenomenon of Acclimatization

Of the studies undertaken at Singapore none was of greater interest, or indeed more elusive of solution, than that intended to determine the 'degree of acclimatization of naval ratings serving in ships in tropical waters'. The conclusions reached were, briefly, these. 'Naturally acclimatized' men in Singapore possessed an ability to withstand the effects of environmental warmth that was superior to that of their counterparts serving in temperate waters who had not previously been exposed to tropical conditions. The tolerance of hot conditions possessed by such naturally acclimatized men was, however, not the greatest they could achieve and on exposure daily to conditions of increasing severity their tolerance was greatly improved. Such 'artificially acclimatized' men then possessed the same degree of tolerance of hot conditions as those men who had been similarly 'artificially acclimatized' at the National Hospital in London. The acclimatized subjects used in the experiments in London thus possessed a greater degree of acclimatization than that possessed by naval ratings serving in the tropics.

These findings deal exclusively with the degree of acclimatization; they say nothing of the nature or mechanism of acclimatization. It is a commonplace observation that the newcomer to a hot climate is more distressed than the established resident. His face is flushed, he appears to sweat more profusely than those who have been exposed to the climate for longer and his capacity for work, especially physical work, is diminished. It is an equally commonplace observation that in a very short time a change occurs in the newcomer; he is less distressed by the heat and his capacity for work is increased. It is to this change that we apply the term acclimatization or, more specifically, acclimatization to heat, it being implied that *mutatis mutandis* a comparable change occurs on exposure to a cold environment.

A formal definition of acclimatization is therefore as follows. Acclimatization is an adaptative process which results in a diminution of the physiological strain produced by the application of a constant environmental stress. However, in the process of natural acclimatization as it occurs in those who move from a temperate to a tropical climate, although it may be obvious that the physiological strain diminishes, it is not so certain that the environmental stress remains constant. There is a large behavioural component in the process of natural acclimatization—the subject discards superfluous clothing, perhaps takes less exercise, or performs the same amount of work with an economy of muscular effort. It is for this reason that the experiments described in Chapter 5, in which the performance of subjects at Singapore is compared with that of similar subjects at Oxford, assume such particular importance. They showed clearly that when the environmental stress is kept constant by eliminating any differences in behaviour, men naturally acclimatized to heat exhibit less physiological strain than those not so acclimatized when the two groups are exposed to the same hot conditions, thus demonstrating that acclimatization to heat involves more than a change in behaviour. Furthermore, the differences between the physiological behaviour of these two groups of men were precisely those that are observed when the behaviour of a group of men before artificial acclimatization is compared with their behaviour after it.

Of the underlying changes in acclimatization we know little, but we recognise some of the manifestations—a difference in response is appreciated though the means whereby the difference is brought about are not understood. It is usually agreed that with acclimatization the increase in body temperature and pulse rate which occurs with work in a warm environment decreases, as does the concentration of sodium chloride in the sweat, whilst the amount of sweat produced is increased.

It is instructive to consider these changes from a teleological point of view. That there should be a fall in both the deep and superficial body temperature is satisfying in that it accords with the view that the changes are purposive. The protection of the deep-body temperature is in agreement with the usual concepts of body temperature regulation, and a reduction in the skin temperature is associated with comfort. The reduction in the heart rate can be taken as indicating that the maintenance of thermal equilibrium has been achieved with a lesser strain on the cardio-vascular system. (Indeed, the brunt of thermal stress appears to be borne by the cardio-vascular system.) The reduction in the sodium chloride in sweat can also be seen to be purposive. It results in a conservation of the sodium chloride of the body and it facilitates the evaporation of sweat (see p. 190). The increased rate of sweating is, on the other hand, not so satisfying from a teleological point of view—an economy of sweating with a conservation of body-water would appear to be indicated.

There are other reasons why the increased secretion of sweat appears anomalous. If the amount of sweat secreted is used as a measure of physiological strain, there is the difficulty which presents itself when it is observed that with increasing acclimatization, when the physiological strain is diminishing, there is an increase in the output of sweat. If sweat *per se* is a measure of strain, then strain increases with acclimatization. The careful definition of the P4SR Index in terms of the sweat lost by fit *acclimatized* young men does not altogether avoid this difficulty.

If the skin temperature is lower in the acclimatized than in the unacclimatized, then the heat gained from the environment by the former will be greater than that gained by the latter and it would be expected that, consequently, a greater output of sweat will be required by the former to achieve thermal balance. Indeed it was shown in Chapter 5 that the increased sweat loss in the Singapore subjects was in a large measure accounted for by the increase in heat gain due to their lower skin temperature. The sweat loss, however, is not always constantly related to the maintenance of thermal balance. It was observed, for instance, in Series II that following the period of acclimatization there was a marked decrease in the rise in rectal temperature with work, although this was accompanied by a decline in the rate of sweating.

It will be noted that in this case acclimatization was accompanied by a fall in sweat rate, and this raises the question of whether an increase in sweating is the constant accompaniment of acclimatization that it is said to be. The experience at Singapore was that it is not. In Series VII, for example, four subjects underwent a uniformity trial at dry-bulb temperature 100°F, wet-bulb temperature 85·3°F and an air speed of 100 ft./min. They wore shorts and followed the usual routine for working subjects. They then were acclimatized by daily work in the heat for a period of 12 days and then underwent a second uniformity trial. At the conclusion of the series of experiments they were submitted to a third uniformity trial. On the first occasion the mean sweat loss was 2·5 l.; on the second occasion it was 2·3 l.—only one man showed an increase and three showed a decrease; on the third occasion it was again 2·3 l. and one subject showed a small increase, the remaining three very little change. There was, however, a fall in rectal temperature following acclimatization despite the diminution of the sweat loss. A similar series of three uniformity trials was performed in the experiments on jungle uniforms (p. 180). The mean sweat loss in the pre-acclimatization trial was 1·19 l. After acclimatization this rose to 1·45 l., but at the conclusion of the experiment it had fallen again to 1·24 l., which was not significantly different from the pre-acclimatization value. It may be added that there was no reason to suspect that the acclimatization status of the men deteriorated during the course of the experiment.

Observations such as these suggest that perhaps the increased rate of sweating so often observed with acclimatization is a transient phenomenon, the temporary nature of which escaped observation because laboratory experiments were of comparatively brief duration. If this were so, it would be in accordance with the belief that newcomers to the tropics sweat more than established residents.

a belief which does not appear to agree with laboratory observations. It should be pointed out, however, that the amount of visible (that is, unevaporated) sweat present does not necessarily provide a guide to the rate at which sweat is secreted, and there is the further incontrovertible fact that, in the uniformity trials of Oxford-Singapore experiments, the Singapore subjects did secrete more sweat than the Oxford group.

The point has been made that laboratory experiments are in general of relatively brief duration, whereas it could well be that the process of acclimatization is a lengthy process involving perhaps an immediate response which is later modified.

During the performance of the third series of experiments (Series III) at Singapore, uniformity trials were performed before acclimatization, after acclimatization, and thereafter at regular intervals of four weeks throughout the series which was brought to a close with a final uniformity trial. This series of experiments extended over a period of 22 weeks and, as far as is known, is the longest series of experiments of its kind to be performed anywhere. The information provided by these experiments on the changes with time in the response to high temperatures of men carefully maintained in a high state of acclimatization is thought to justify their discussion at some length. (A full account of these experiments is given by Adam, Ellis, John, Lee and Macpherson (1953).)

The first two uniformity trials were performed in the morning only; thereafter trials were performed in duplicate in the morning and in the afternoon. Fig. 41 sets out the mean final pulse rate and mean final rectal temperature for each trial. The expected fall in the pulse rate with acclimatization can be observed and it will be noted that the lower post-acclimatization value persisted throughout the whole period of 22 weeks. There was no difference between the pulse rate of the morning, and that of the afternoon experiments. Acclimatization was

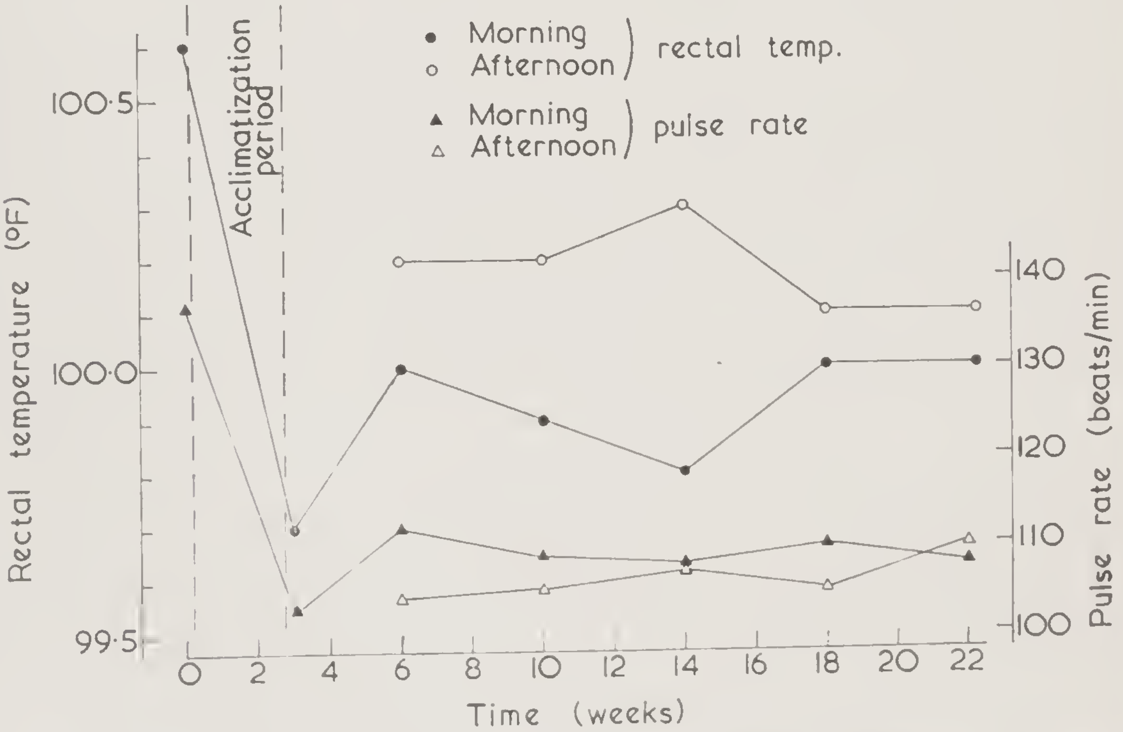

FIG. 41. Series III. Uniformity trials. Mean final rectal temperature and mean final pulse rate for each morning and afternoon experiment.

also accompanied by a fall in rectal temperature which was likewise maintained for the duration of the series of experiments. As would be expected, the afternoon temperature was higher than the morning temperature. The mean difference, 0·24°F, was also close to expectation (p. 199).

Weiner and van Heyningen (1952), who investigated the chloride balance of subjects during acclimatization to heat, concluded that 'about 80 per cent of the changes in sweating, body temperature and pulse rate occurred in the first seven days of exposure' and that 'the first week or two of daily exposure are the crucial ones for examining sweat for changes brought out by acclimatization', a view which is generally accepted. The behaviour of the pulse rate and body temperature of the Series III subjects was in accordance with those views, but the sweating mechanism did not behave as expected.

The serial sweat losses in Series III are set out in Fig. 42. The expected initial increase is observed but it was succeeded by a gradual decline, so that at the conclusion of the series the sweat loss was not far removed from its initial value. The water intake of the subjects is plotted in the same figure and it will be observed that, although water was freely available, the subjects never drank as much water in any experimental period as they lost in sweat. During the fourth trial two subjects, for some unknown reason, refused to drink water they obviously needed, and their sweat output was much reduced in consequence. They did not repeat this behaviour on any subsequent occasion and it has been thought advisable therefore to omit their results on that day. Just as the amount of sweat secreted diminished in the latter part of the series, so did the amount of water drunk. Since the amount of sweat secreted depends upon the water intake (see Chapter 8), it could well be argued that the decline in sweat production merely mirrored a reduction in water intake but for the fact that the initial rise in sweat production which occurred during acclimatizaton was not accompanied by a corresponding increase in the water intake, and the subsequent fall was not exactly reflected in the amount of water drunk.

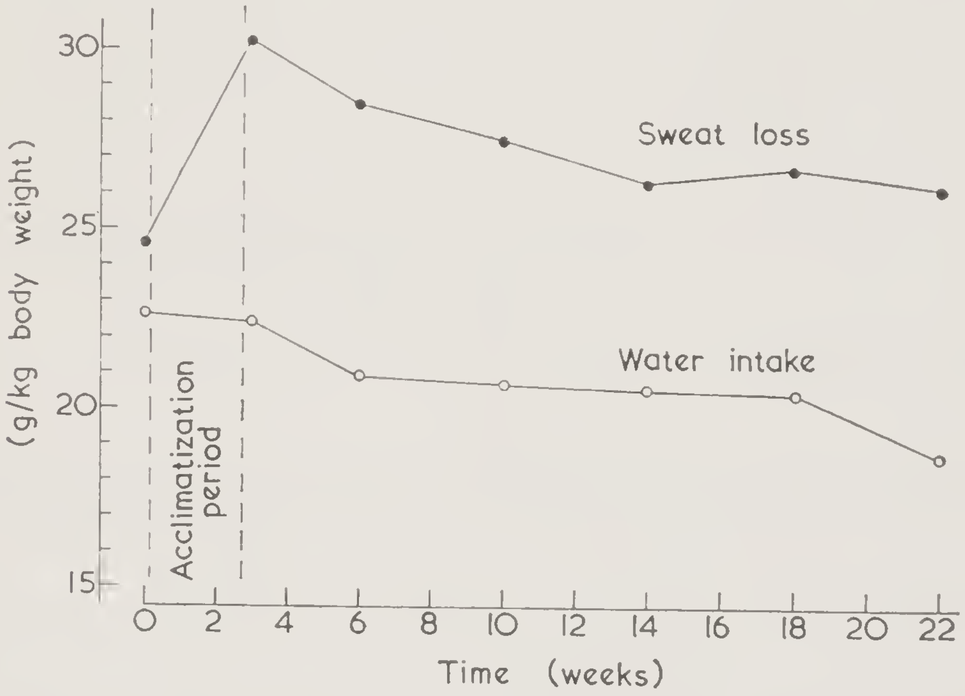

FIG. 42. Series III. Uniformity trials. Mean sweat loss and mean water intake for each experiment.

It is not, however, only the amount of water drunk during the course of the experiment but also the general state of hydration of the subject that might influence the amount of sweat lost. In Fig. 43 it will be seen that after an initial rise the body weight of the subjects declined, the decline becoming steeper in the latter part of the series. The total change is not great, but the day to day changes are statistically highly significant, as also are the morning-afternoon differences. The source of this morning-afternoon difference is of some importance.

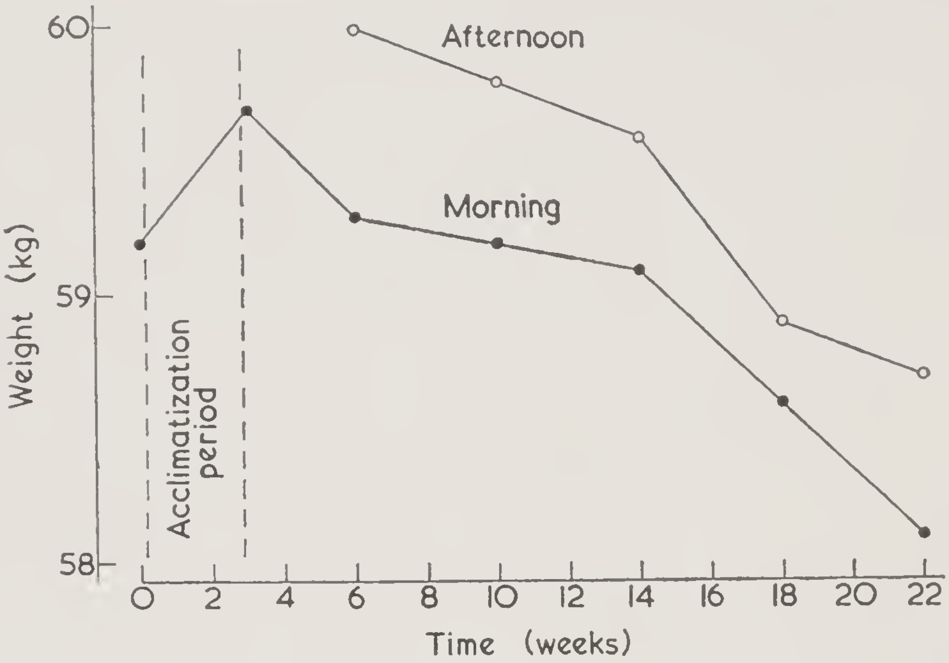

FIG. 43. Series III. Uniformity trials. Mean initial weight for each morning and afternoon experiment.

It so happened from the arrangement of the trials that the opportunity for rehydration after exposure to hot room conditions was much greater for the afternoon than for the morning group; this might well explain the greater weight of the subjects in the afternoon. The afternoon trials also differed from the morning ones in that they followed more closely after a meal, and that the main meal of the day. It is probable that both these factors contributed towards the observed difference in weight; for that matter, they would have a common result as the fluid taken with the meal would contribute towards the hydration of the subjects. If, therefore, the output of sweat was determined by the state of hydration of the subjects and the progressive decline in weight was due to a progressively increasing state of dehydration, it would be expected that the afternoon group would have a greater sweat output than the morning group. This, however, was not found to be so. Therefore it is concluded—largely, it must be admitted, on the grounds of lack of evidence to the contrary—that the increased water loss which accompanies acclimatization is but an immediate adjustment to heat stress. With the passage of time, and more complete acclimatization, adaptation to work in the heat is accomplished with an economy of water loss.

The mean chloride and lactate content of arm-bag sweat collected during the trials (expressed as sodium chloride and lactic acid) is shown in Fig. 44. The amount of lactic acid increased with acclimatization but thereafter showed little change. There was no significant difference between the morning and afternoon experiments. The chloride content behaved differently. It declined sharply with acclimatization and thereafter, except for an inexplicable rise on the third morning trial, showed a steady decline throughout the series. This would seem to indicate, contrary to the views of Weiner and van Heyningen (1952), that the reduction in the chloride content of sweat which accompanies acclimatization is not largely complete in the first few weeks but continues even after 22 weeks. The concentration of salt in sweat is determined by a number of factors other than acclimatization, notably the amount of salt in the diet (McCance, 1936, 1938) and it might be that the fall observed resulted from a steady depletion of the salt content of the body. The circumstances just described, which resulted in a greater opportunity for rehydration before the afternoon trials, would also provide a greater opportunity for the replacement of salt, so it might be expected that there would be a greater salt output in the afternoon trials. On the contrary, the output was significantly less in the afternoon, so that it would seem unlikely that the diminishing chloride output is a sign of chloride deficiency. It would rather seem that it is an expression of continuing adjustment to work in the heat.

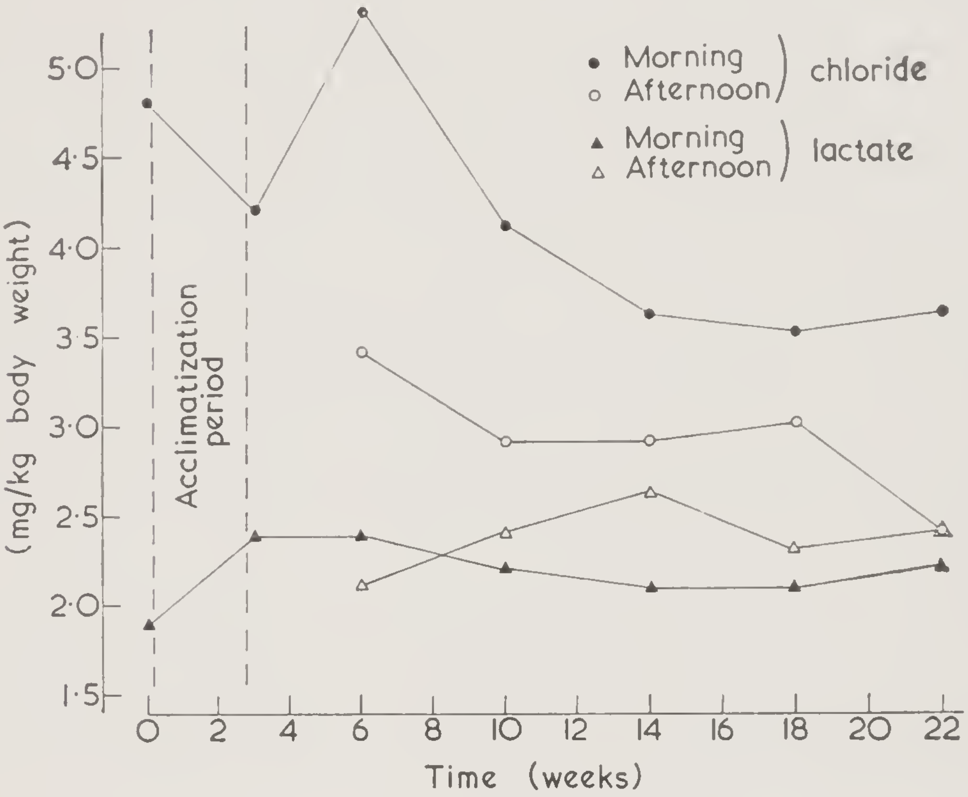

FIG. 44. Series III. Uniformity trials. Mean amounts of chloride (expressed as sodium chloride) and lactate (expressed as lactic acid) collected from the left arm in the first 160 minutes of each morning and afternoon experiment.

No account of acclimatization can be considered complete if no reference is made to the reactions of indigenous tropical inhabitants to heat stress and the manner in which they differ from those of non-indigenous Europeans. The findings in this connection described in the previous chapter therefore assume considerable importance. The conclusions reached were that if, in the different races examined, the subjects were of similar age and nutritional status and had been accustomed to the same type of work for a number of years in the same hot climate, the differences in the physiological responses to work in the heat which could be attributed to racial differences would be small.

The far-reaching nature of the finding that the indigenous inhabitants of the tropics do not differ from Europeans in their physiological response to hot environments need not be stressed further, but additional studies are needed to confirm this finding. As for their degree of acclimatization, it would probably be fair to say that the indigenous inhabitants possessed the same degree of tolerance of hot conditions as did the 'naturally acclimatized' sailors with whom they were compared. Their tolerance of heat would therefore be inferior to that of those experimental subjects who were further acclimatized artificially. There is, however, nothing to suggest that further exposure of the indigenous inhabitants to higher levels of heat stress would not further increase their degree of acclimatization.

The comparison between Europeans and Asians did reveal one difference in the behaviour of the two groups. The Asians when exposed to heat exhibited a much smaller salt and water turnover. The amount of sweat lost by the Asians was always less than that lost by the Europeans in the same conditions and the output of chloride was also less. The reasons for this quite profound difference require further investigation.

The results of these experiments, taken in conjunction with the results of the uniformity trials of Series III just described, lend support to the conclusion that long-term acclimatization to hot environments is accompanied by an economy of water and salt turnover. That there should be such an economy in salt metabolism is in agreement with the finding of Ladell (1951) and is what one might expect from the hypothesis of Conn (Conn, Johnston & Louis, 1946) that the process of acclimatization to heat is mediated by adrenal cortical hormones.

The note of uncertainty on which this review necessarily ends serves to point the way to the most important work yet to be done on the effects of hot environments on man—the determination of the fundamental mechanism of acclimatization and the effect of exposure to heat over a period, not of hours or weeks, but of years, or even generations.

TABLES TO THE TEXT

Tables to Chapter 2

TABLE 1

Series I. Summary of analyses of variance of initial rectal temperature and initial pulse rate throughout the series

Source of variation	Degrees of freedom	Variance ratio (F) Rectal temperature	Variance ratio (F) Pulse rate
Morning/afternoon	1	99·94***	3·63
Early/late†	1	5·47*	0·34
Subjects	11	5·41***	13·28***
Error	226		

*** Significant at 0·1% level
* Significant at 5% level
† Early: from 19th Jan. to 17th March
late: from 25th March to 28th April

TABLE 2

Series I. Results of uniformity trials held before and after the main experiments. The environmental conditions were dry-bulb temperature 90°F, wet-bulb temperature 86°F, air speed 50 ft./min

The bracketed figures give the numbers of subjects who showed a change in the same direction as the average

	Before Ser. I (17 & 18 Jan.)	After Ser. I 3 & 5 May	After Ser. I 9 & 10 May
No. of subjects	12	12	11
Mean total sweat loss (kg)	1·474	1·887(11)	1·823(10)
Mean rectal temperature after Work III (°F)	100·73	100·47(8)	100·19(10)
Mean final pulse rate (beats/min)	113·8	115·3(7)	108·0(9)

TABLE 3

Series I. Total sweat loss. Mean values (grams) for climate and work-clothing effects. No corrections necessary for personal differences

Section A

Climate

Air speed (ft/min)	Dry-bulb temp. (°F) 90	Dry-bulb temp. (°F) 120	Wet-bulb temp. (°F) 80	Wet-bulb temp. (°F) 85	Mean
40	1255	3152	1964	2444	2204
100	1053	2707	1768	1992	1880
300	947	3016	2045	1918	1982
500	805	3440	2041	2204	2122
Mean	1015	3079	1955	2140	

Standard error for a single mean 53

Work-clothing

	Shorts	Overalls	Mean
Working	2582	2721	2652
Resting	1475	1409	1442
Mean	2028	2065	

Standard error for a single mean 38

Section B

Climate (air speed 300 ft./min)

Wet-bulb temp. (°F)	Dry-bulb temp. (°F) 90	Dry-bulb temp. (°F) 100	Dry-bulb temp. (°F) 120	Mean
80	990	1606	3101	1899
83	969	1577	3015	1854
85	904	1734	2932	1856
88	1115	1867	3666	2216
Mean	994	1696	3174	1956

Standard error for a single mean 66

Work-clothing

	Shorts	Overalls	Mean
Working	2350	2612	2481
Resting	1477	1387	1432
Mean	1913	1999	

Standard error for a single mean 38

TABLE 4

Series I. Sweat loss. Interactions of climate and work-clothing. Mean values (grams), corrected for differences between subjects in the uniformity trials

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting
S − O = shorts—overalls
W − R = working—resting

Section A

Air speed × dry-bulb temperature × work-clothing

Air speed (ft./min)	Dry-bulb temperature 90°F					Dry-bulb temperature 120°F				
	a	b	c	d	S − O	a	b	c	d	S − O
40	1791	494	2045	691	− 226	3746	2177	4155	2531	− 382
100	1499	459	1705	550	− 148	3234	2120	3593	1881	− 60
300	1305	459	1493	531	− 130	3601	2698	3531	2236	266
500	1198	303	1372	347	− 109	4283	3095	3876	2504	499

All standard errors for single means are between 106 and 110

Air speed × wet-bulb temperature × work-clothing

Air speed (ft./min)	Wet-bulb 85°F — Wet-bulb 80°F						
	a	b	c	d	S − O	W − R	Interaction
40	849	179	339	555	67	227	443
100	29	− 65	671	261	− 484	252	− 158
300	− 21	− 213	− 61	− 251	21	173	19
500	86	82	448	34	− 157	209	− 205
Mean	236	− 4	349	159	− 138	215	12

All standard errors for single means are between 150 and 160

Section B

Dry-bulb temperature × work-clothing (air speed 300 ft./min)

Dry-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
90	1416	444	1536	582	− 129	963	9
100	2055	1213	2378	1138	− 124	1041	− 199
120	3578	2775	3921	2440	− 4	1142	− 329

All standard errors for single means are between 65 and 73

Wet-bulb temperature × work-clothing (air speed 300 ft./min)

Wet-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
80	2329	1490	2394	1385	21	925	− 86
83	2190	1461	2430	1335	− 57	912	− 183
85	2335	1420	2421	1251	42	1043	− 128
88	2545	1539	3203	1579	− 349	1315	− 309

All standard errors for single means are between 75 and 84

TABLE 5

Series I. Final rectal temperature. Mean values (°F) for significant climate and work-clothing effects. No corrections necessary for personal differences

Section A

Climate

Wet-bulb temp. (°F)	Dry-bulb temp. (°F)		Mean
	90	120	
80	99·7	100·3	100·0
85	99·8	100·8	100·3
Mean	99·7	100·5	100·2

Standard error for a single mean 0·05

Work-clothing

	Shorts	Overalls	Mean
Working	100·8	100·9	100·9
Resting	99·4	99·4	99·4
Mean	100·1	100·2	100·2

Standard error for a single mean 0·07

Section B

Climate (air speed 300 ft./min)

Wet-bulb temp. (°F)	Dry-bulb temp. (°F)			Mean
	90	100	120	
80	99·7	100·1	100·3	100·0
83	99·7	100·1	100·4	100·0
85	99·7	100·0	100·6	100·1
88	99·9	100·1	100·9	100·3
Mean	99·7	100·0	100·6	100·1

Standard error for a single mean 0·11

Work-clothing

	Shorts	Overalls
Working	100·8	100·8
Resting	99·5	99·4

Shorts—overalls 0·05
Working—resting 1·3

Standard error for a single mean 0·06

TABLE 6

Series I. Final rectal temperature. Interactions of climate and work-clothing. Mean values (°F), corrected for differences between subjects in the uniformity trials

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting
S − O = shorts—overalls
W − R = working—resting

Section A

Dry-bulb temperature × work-clothing

Dry-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
90	100·2	99·0	100·5	99·7	− 0·2	1·3	− 0·1
120	101·3	99·7	101·3	99·7	0·0	1·6	0·0

Standard error for a single mean 0·07

Wet-bulb temperature × work-clothing

Wet-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
80	100·6	99·3	100·6	99·3	0·0	1·3	0·0
85	100·9	99·5	101·2	99·5	− 0·1	1·6	− 0·1

Standard error for a single mean 0·07

Air speed × working-clothing

Air speed (ft./min)	a	b	c	d	S − O	W − R	Interaction
40	101·0	99·4	101·3	99·6	− 0·3	1·7	0·0
100	100·7	99·3	101·1	99·4	− 0·3	1·6	− 0·2
300	100·8	99·4	100·8	99·3	0·0	1·4	0·0
500	100·5	99·4	100·5	99·3	0·0	1·2	0·0

Standard error for a single mean 0·10

Section B

Dry-bulb temperature × work-clothing (air speed 300 ft./min)

Dry-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
90	100·3	99·1	100·5	99·1	− 0·1	1·3	− 0·1
100	100·7	99·4	100·8	99·4	0·0	1·3	0·0
120	101·5	99·9	101·2	99·7	0·3	1·6	0·0

Standard error for a single mean 0·10

Wet-bulb temperature × work-clothing (air speed 300 ft./min)

Wet-bulb temp. (°F)	a	b	c	d	S − O	W − R	Interaction
80	100·6	99·4	100·7	99·4	0·0	1·2	0·0
83	100·8	99·4	100·5	99·5	0·1	1·2	0·2
85	100·9	99·4	100·9	99·2	0·1	1·6	− 0·2
88	100·9	99·6	101·2	99·4	0·0	1·6	− 0·2

Standard error for a single mean 0·12

TABLE 7

Series I. Final standing pulse rate. Mean values (beats/min) for climate and work-clothing effects. No corrections necessary for personal differences

Section A

Climate

Wet-bulb temp. (°F)	Dry-bulb temp. (°F) 90	120	Mean
80	96·1	118·0	107·0
85	100·4	129·4	114·9
Mean	98·2	123·7	111·0

Air speed (ft./min)	
40	117·5
100	108·3
300	110·2
500	107·7
Mean	111·0

Work-clothing

	Shorts	Overalls	Mean
Working	120·5	128·3	124·4
Resting	96·4	98·5	97·5
Mean	108·5	113·4	110·9

Standard error for a single mean 3·52

Section B

Climate (air speed 300 ft.min)

Wet-bulb temp. (°F)	Dry-bulb temp. (°F) 90	100	120	Mean
80	95·5	99·0	116·8	103·8
83	95·0	103·7	121·3	106·7
85	97·2	107·2	133·2	112·5
88	100·0	109·5	127·7	112·4
Mean	96·9	101·8	124·7	108·8

Standard error for a single mean 3·60

Work-clothing

	Shorts	Overalls	Mean
Working	120·7	125·8	123·3
Resting	95·1	93·8	94·5
Mean	107·9	109·8	108·9

Standard error for a single mean 2·07

TABLE 8

Series I. Final standing pulse rate. Interactions of climate and work-clothing. Mean values (beats/min), corrected for differences between subjects in the uniformity trials

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting
S − O = shorts—overalls
W − R = working—resting

Section A

Air speed × dry-bulb temperature × work-clothing

Air speed (ft./min)	Dry-bulb temperature 90°F a	b	c	d	S − O	Dry-bulb temperature 120°F a	b	c	d	S − O
40	112·1	95·8	127·4	94·2	− 6·9	141·5	100·1	159·8	109·1	− 13·7
100	100·8	87·2	111·4	88·7	− 6·0	133·1	96·1	139·8	108·8	− 9·7
300	100·8	85·5	110·1	85·4	− 4·6	141·1	107·7	145·2	105·8	− 1·1
500	100·3	84·3	101·0	85·8	− 1·1	134·0	114·3	131·7	110·3	3·2

Standard error for a single mean 4·98

Section B

Dry-bulb temperature × work-clothing (air speed 300 ft./min)

Dry-bulb temp. (°F)	a	b	c	d	S − O	W − R
90	104·2	87·6	109·6	86·3	− 2·0	20·0
100	114·3	92·2	123·0	89·8	− 3·2	27·6
120	143·5	105·5	144·8	105·4	− 0·6	38·6

Standard error for a single mean 3·58

Wet-bulb temperature × work-clothing (air speed 300 ft./min)

Wet-bulb temp. (°F)	a	b	c	d	S − O	W − R
80	112·4	91·9	121·8	89·0	− 3·3	26·6
83	121·4	95·4	117·1	92·7	− 3·5	25·2
85	122·5	94·8	127·9	99·8	2·7	25·4
88	126·3	93·1	136·3	93·8	5·4	37·9

Standard error for a single mean 4·14

TABLE 9

Series I, Section A. Total sweat loss. Mean values (grams) observed (O) *and expected on the basis of the P4SR nomogram* (E)

a = shorts working
b = shorts resting
c = overalls working
d = overalls working
S − O = shorts—overalls
W − R = working—resting

Air-speed (ft./min)		a	b	c	d	S − O	W − R	a	b	c	d	S − O	W − R
		Dry-bulb temp. 90 F, wet-bulb temp. 80 F						*Dry-bulb temp. 90 F, wet-bulb temp. 85°F*					
	O	1523	350	1734	634	−248	1137	2058	638	2358	749	−206	1515
40	E	1218	514	1776	787	−416	847	1414	572	2147	885	−523	1052
	O − E	305	−164	−42	−153	168	290	644	66	211	−136	317	463
	O	1349	509	1517	328	7	1015	1648	409	1894	773	−305	1180
100	E	1081	425	1609	680	−392	793	1208	455	1824	729	−445	924
	O − E	268	84	−92	−352	399	222	440	−46	70	44	140	256
	O	1268	560	1396	735	−152	685	1342	357	1590	328	−110	1124
300	E	1032	377	1570	641	−401	792	1100	377	1727	650	−450	900
	O − E	236	183	−174	94	249	−107	242	−20	−137	−322	340	224
	O	1197	222	1264	385	−115	927	1199	384	1480	309	−103	993
500	E	905	259	1433	514	−392	783	1052	328	1658	602	−440	890
	O − E	292	−37	−169	−129	277	144	147	56	−178	−293	337	103
		Dry-bulb temp. 120 F, wet-bulb temp. 80 F						*Dry-bulb temp. 120 F, wet-bulb temp. 85 F*					
	O	3165	2144	4128	2034	−427	1558	4327	2211	4183	3030	−338	1635
40	E	2989	2216	3585	2499	−440	930	3302	2343	4123	2676	−577	1203
	O − E	176	−72	543	−465	13	628	1025	−132	60	354	239	432
	O	3356	2134	3109	1843	269	1244	3113	2107	4077	1919	−388	1582
100	E	2920	2245	3468	2499	−401	822	3086	2323	3761	2597	−475	964
	O − E	436	−111	−359	−656	670	422	27	−216	316	−678	87	618
	O	3660	2809	3690	2246	267	1148	3543	2587	3372	2226	266	1051
300	E	3282	2607	3820	2871	−401	812	3419	2636	4075	2920	−470	969
	O − E	378	202	−130	−625	668	336	124	−49	−703	−694	736	82
	O	4200	3094	3535	2431	664	1105	4367	3093	4217	2577	333	1457
500	E	3488	2822	4026	3086	−401	803	3595	2832	4231	3116	−460	939
	O − E	712	272	−491	−655	1065	302	772	261	−14	−539	793	518

		a	b	c	d	S − O	W − R
All	O	2582	1476	2722	1409	−37	1210
climate	E	2196	1462	2803	1736	−441	901
means	O − E	386	14	−81	−327	404	309

The standard error of an individual entry is 150, and of the a, b, c and d column means 37

TABLE 10

Effect of severe environmental conditions on ability to complete task. Comparison between data of Singapore (Series I) and of London (Dunham et al.) for groups containing at least one man who failed

a = shorts working
c = overalls working
d = overalls resting

	No. subjects		P4SR	Effect. temp. (°F)	Work-clothing	Wet-bulb temp. (°F)	Dry-bulb temp. (°F)	Air speed (ft./min)
	Total in group	Failed to complete trial						
Singapore (Series I)	1	1	3·10	94·0	d	94	95	80
	5	4	4·65	91·8	a	92	93	40
	4	1*	4·69	94·0	c	88	120	80
	4	1*	4·87	92·6	c	85	120	40
	2	2	6·15	93·6	a	94	95	80
	3	3	9·39	94·0	c	94	95	80
London (Dunham *et al*)	4	1	4·35	94·4	a	88	120	50
	2	1	5·15	92·2	a	95	96	500
	4	3	5·59	94·5	c	88	120	50
	5	4	6·10	93·7	a	94	95	75
	7	1	6·39	90·2	c	90	92	10

*The same subject, who had a very low tolerance of heat, collapsed in both cases.

TABLE 11

Series I. Section A. Total sweat loss. Mean values (grams) observed (O) *and expected on the basis of the Effective Temperature Scale* (E)

a = short working
b = shorts resting
c = overalls working
d = overalls resting
S − O = shorts—overalls
W − R = working—resting

Air speed (ft./min)		a	b	c	d	S − O	W − R	a	b	c	d	S − O	W − R
		Dry-bulb temp. 90°F, wet-bulb temp. 80°F						*Dry-bulb temp. 90°F, wet-bulb temp. 85°F*					
40	O	1523	350	1734	634	−248	1137	2058	638	2358	749	−206	1515
	E	1190	1190	1441	1441	−251	0	1837	1837	2003	2003	−166	0
	O − E	333	−840	293	−807	3	1137	221	−119	355	−1245	−40	1515
100	O	1349	509	1517	328	7	1015	1648	409	1894	773	−305	1180
	E	1003	1003	1295	1295	−292	0	1670	1670	1878	1878	−208	0
	O − E	346	−494	222	−967	299	1015	−22	−1261	16	−1105	−97	1180
300	O	1268	560	1396	735	−152	685	1342	357	1590	328	−110	1124
	E	399	399	920	920	−521	0	1128	1128	1482	1482	−354	0
	O − E	869	161	476	−185	369	685	214	−771	108	−1154	244	1124
500	O	1197	222	1264	385	−115	927	1199	384	1480	309	−103	993
	E	−18	−18	607	607	−625	0	690	690	1149	1149	−459	0
	O − E	1215	240	657	−222	510	927	509	−306	331	−840	356	993
		Dry-bulb temp. 120°F, wet-bulb temp. 80°F						*Dry-bulb temp. 120°F, wet-bulb temp. 85°F*					
40	O	3165	2144	4128	2034	−427	1558	4327	2211	4183	3030	−338	1635
	E	2712	2712	2816	2816	−104	0	3316	3316	3316	3316	0	0
	O − E	453	−568	1312	−782	−323	1558	1011	−1105	867	−286	−338	1635
100	O	3356	2134	3109	1843	269	1244	3113	2107	4077	1919	−388	1582
	E	2670	2670	2774	2774	−104	0	3254	3254	3295	3295	−41	0
	O − E	686	−536	335	−931	373	1244	−141	−1147	782	−1376	−347	1582
300	O	3660	2809	3690	2246	267	1148	3543	2587	3372	2226	266	1051
	E	2566	2566	2649	2649	−83	0	3108	3108	3149	3149	−41	0
	O − E	1094	243	1041	−403	350	1148	435	−521	223	−923	307	1051
500	O	4200	3094	3535	2431	664	1105	4367	3093	4217	2577	333	1457
	E	2483	2483	2608	2608	−125	0	3045	3045	3066	3066	−21	0
	O − E	1717	611	927	−177	789	1105	1322	48	1151	−489	354	1457

		a	b	c	d	S − O	W − R
All	O	2582	1476	2722	1409	−37	1210
climate	E	1941	1941	2149	2149	−208	0
means	O − E	641	−465	573	−740	171	1210

The standard error of an individual entry is 150, and of the a, b, c and d column means 37

TABLE 12

Series I. Comparison of the average correlations between the physiological effects and the P4SR Index and the Effective Temperature Scale within the four work-clothing groups with those for all four groups combined

	P4SR		Effective temperature*	
	Within groups	Groups combined	Within groups	Groups combined
Total sweat … … …	0·98	0·96	0·93 (0·91)	0·80 (0·78)
Final rectal temperature …	0·84	0·74	0·90 (0·86)	0·48 (0·48)
Final pulse rate … … …	0·86	0·84	0·90 (0·86)	0·63 (0·63)

*These values allow for non-linearity of the regressions; the values in parentheses are the 1st order correlation coefficients.

TABLE 13

Series I. Mean final rectal temperatures and standing pulse rates and 'upper 5% limits' for working and resting subjects at assigned P4SR values

Working subjects					Resting subjects				
P4SR	Final rectal temperature (°F)		Standing pulse rate (beats/min)		P4SR	Final rectal temperature (°F)		Standing pulse rate (beats/min)	
	Mean	Upper 5% limit	Mean	Upper 5% limit		Mean	Upper 5% limit	Mean	Upper 5% limit
3·0	100·9	101·4	133	145	4·0	100·2	100·5	118	128
3·5	101·1	101·6	141	153	4·5	100·3	100·6	122	132
4·0	101·3	101·8	148	160	5·0	100·5	100·8	126	136

Tables to Chapter 3

TABLE 14

Series II. Results of the uniformity trials

UT$_1$, UT$_2$, UT$_3$, UT$_4$ = First, second, third and fourth uniformity trials

Team	Subject	Total sweat loss (grams)				Rectal temperature after third work period (°F)				Pulse rate after third work period (beats/min)			
		UT$_1$	UT$_2$	UT$_3$	UT$_4$	UT$_1$	UT$_2$	UT$_3$	UT$_4$	UT$_1$	UT$_2$	UT$_3$	UT$_4$
A	1	2130	2520	2145	2684	101·4	100·4	100·5	100·3	156	156	124	146
	2	2080	2630	2775	2610	101·5	101·3	100·8	101·1	160	156	142	144
	3	1770	2150	2390	1707	100·0	101·4	100·7	101·1	164	176	128	130
	4	1800	2130	2530	2565	101·4	101·2	101·1	101·0	142	132	122	124
B	1	2100	2500	3030	2509	100·6	100·6	101·0	100·0	132	136	136	138
	2	2740	3000	3285	2635	100·2	100·7	100·3	100·1	144	128	124	120
	3	2100	2530	2225	1700	100·2	100·2	100·1	100·2	120	120	110	112
	4	1420	1750	1810	1435	100·9	100·9	100·8	100·1	128	132	124	128
C	1	2170	2655	1940	2200	101·5	101·6	100·6	100·5	148	140	120	144
	2	1950	2280	1990	2500	100·6	100·5	99·9	100·0	132	132	132	128
	3	1640	2680	2160	2310	100·9	100·5	99·6	100·0	146	156	132	144
	4	1990	2680	2695	2400	101·5	101·0	100·5	101·1	152	140	152	132
Mean		1991	2459	2415	2271	100·9	100·9	100·5	100·5	144	142	129	133
Range		1420 to 2740	1750 to 3000	1810 to 3285	1435 to 2684	100·0 to 101·5	100·2 to 101·6	99·6 to 101·1	100·0 to 101·1	120 to 164	120 to 176	110 to 152	112 to 146

TABLE 15

Series II. Comparison of findings in the four uniformity trials, 't' values and their significance

UT$_1$, UT$_2$, UT$_3$, UT$_4$ = First, second, third and fourth uniformity trials

	't' values				
	UT$_1$ – UT$_2$	UT$_2$ – UT$_3$	UT$_3$ – UT$_4$	UT$_1$ – UT$_4$	UT$_2$ – UT$_4$
Total sweat loss	7·58***	0·38	1·15	2·65*	1·83
Rectal temperature after third work period	0·20	3·05*	0·25	2·54*	3·97**
Pulse rate after third work period	0·67	2·84*	1·08	3·37**	2·62*

* Significant at 5% level
** Significant at 1% level
*** Significant at 0·1% level

TABLE 16

Series II. Mean values (°F) for significant differences between the rectal temperatures after the third work periods of Part 1 and Part 2

Air speed work-clothing interaction

Work-clothing	Air speed (ft./min)			Mean
	20	100	300	
Shorts working	0·49	0·31	0·44	0·41
Shorts resting	0·17	0·08	0·45	0·23
Overalls working	0·45	1·15	0·24	0·61
Overalls resting	0·52	−0·18	0·08	0·14
Mean ...	0·41	0·34	0·34	

Temperature work-clothing interaction

Work-clothing	Dry- and wet-bulb temperatures (°F)			
	90/83	90/88	120/83	120/88
Shorts working	0·18	0·31	0·36	0·81
Shorts resting	0·21	−0·06	0·32	0·46
Overalls working	0·32	0·61	0·69	0·83
Overalls resting	0·07	0·11	0·20	0·18
Mean ...	0·19	0·24	0·39	0·57

TABLE 17

Series II. Mean values (beats/min) for significant differences between the pulse rates after the third work periods of Part 1 and Part 2

Temperature air speed interaction

Dry- and wet-bulb temperatures (°F)	Air speed (ft./min)			Mean
	20	100	300	
90/83	9	3	10	8
90/88	7	20	5	11
120/83	3	18	13	11
120/88	8	9	4	7
Mean	7	12	8	

Air speed work-clothing interaction

Work-clothing	Air speed (ft./min)			Mean
	20	100	300	
Shorts working	9	16	11	12
Shorts resting	11	1	10	7
Overalls working	5	22	8	12
Overalls resting	3	10	3	5
Mean ...	7	12	8	

Temperature work-clothing interaction

Work-clothing	Dry- and wet-bulb temperatures (°F)				Mean
	90/83	90/88	120/83	120/88	
Shorts working	10	19	19	0	12
Shorts resting	8	4	7	11	7
Overalls working	12	16	13	0	12
Overalls resting	0	4	5	12	5
Mean	8	11	11	7	

TABLE 18

Series II, Part 1. Total sweat loss. Mean values (grams) for all treatment combinations

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting

Section A

Air speed (ft./min)	Work-clothing	Dry- and wet-bulb temperatures (°F)			
		90/83	90/88	120/83	120/88
20	a	1602	3435	3907	6050
	b	704	803	2208	3334
	c	2617	4267	5878	6011
	d	887	1411	3179	4177
Mean		1453	2479	3793	4893
100	a	1483	2438	3687	5063
	b	397	569	2475	3044
	c	1888	3560	4128	4876
	d	973	876	2180	3341
Mean		1185	1861	3118	4081
300	a	1558	1672	4271	4002
	b	541	453	2925	2868
	c	1640	2327	3919	5274
	d	587	748	2292	3328
Mean		1082	1300	3352	3868
500	a	1405	1455	4288	4164
	b	575	377	2902	3388
	c	1717	2693	4112	4631
	d	512	562	2467	3092
Mean		1052	1272	3442	3819

Section B (air speed 20 ft./min)

Dry-bulb temp. (°F)	Work-clothing	Wet-bulb temperature (°F)			
		80	83	85	88
90	a	1692	1602	2446	3435
	b	592	704	609	803
	c	2591	2617	3015	4267
	d	583	887	1425	1411
Mean		1365	1453	1874	2479
120	a	3012	3907	4548	6050
	b	1961	2208	3064	3334
	c	4658	5878	4835	6011
	d	2250	3179	3864	4177
Mean		2970	3793	4078	4893

TABLE 19

Series II, Part 1. Final rectal temperature. Mean values (°F) for all treatment combinations

a = shorts working
b = shorts resting
c = overalls workng
d = overalls resting

Section A

Air speed (ft./min)	Work-clothing	Dry- and wet-bulb temperatures (°F)			
		90/83	90/88	120/83	120/88
20	a	99·7	100·7	100·5	102·9
	b	98·9	99·7	99·9	100·7
	c	100·1	101·5	101·5	103·5
	d	99·4	99·9	100·0	101·5
Mean		99·5	100·5	100·5	102·1
100	a	99·8	100·0	100·3	101·3
	b	99·2	99·4	99·8	99·7
	c	100·2	100·9	101·3	102·8
	d	99·1	98·8	99·9	99·9
Mean		99·6	99·8	100·3	100·9
300	a	99·9	100·0	100·9	101·4
	b	99·3	99·3	99·6	100·0
	c	100·3	100·6	101·2	101·9
	d	99·1	99·4	99·5	99·9
Mean		99·6	99·8	100·3	100·8
500	a	100·0	100·2	100·8	102·3
	b	98·9	98·8	100·4	100·0
	c	99·7	99·9	101·0	101·4
	d	99·1	99·4	100·0	99·6
Mean		99·4	99·6	100·5	100·8

Section B (air speed 20 ft./min)

Dry-bulb temp. (°F)	Work-clothing	Wet-bulb temperature (°F)			
		80	83	85	88
90	a	100·5	99·7	100·2	100·7
	b	99·1	98·9	99·0	99·7
	c	99·7	100·1	100·7	101·5
	d	99·4	99·4	99·3	99·9
Mean		99·7	99·5	99·8	100·5
120	a	100·5	100·5	100·7	102·9
	b	99·5	99·9	99·5	100·7
	c	101·1	101·5	102·8	103·5
	d	99·6	100·0	100·1	101·5
Mean		100·2	100·5	100·8	102·1

TABLE 20

Series II, Part 1. Standing pulse rate after the third work period. Mean values (beats/min) for all treatment combinations

a = shorts working
b = shorts resting
c = overalls working
d = overalls resting

Section A

Air speed (ft./min)	Work-clothing	Dry- and wet-bulb temperatures (°F)			
		90/83	90/88	120/83	120/88
20	a	128	161	138	167
	b	92	95	105	126
	c	131	156	167	177
	d	99	99	109	142
Mean		112	128	130	153
100	a	103	152	143	172
	b	81	87	101	115
	c	129	168	175	158
	d	89	95	105	128
Mean		101	125	131	143
300	a	105	117	159	157
	b	97	95	113	111
	c	117	133	165	168
	d	83	97	104	120
Mean		101	111	135	139
500	a	115	115	160	156
	b	84	81	109	117
	c	107	141	171	163
	d	87	92	104	120
Mean		98	107	136	139

Section B (air speed 20 ft./min)

Dry-bulb temp. (°F)	Work-clothing	Wet-bulb temperature (°F)			
		80	83	85	88
90	a	117	128	131	161
	b	81	92	89	95
	c	120	131	139	156
	d	84	99	109	99
Mean		101	112	117	128
120	a	145	138	156	161
	b	107	105	109	126
	c	159	167	179	177
	d	100	109	123	142
Mean		128	130	142	153

Tables to Chapter 4

TABLE 21

Series III, Section A. Total sweat loss. Mean values (grams) for significant effects

Climate effects

Temperature × air speed

Air speed (ft./min)	Dry-bulb 90 F	Dry-bulb 120 F	Mean
20	1626	3719	2672
100	1226	3275	2251
300	1035	3216	2125
500	900	3475	2188
Mean	1197	3421	2309

Humidity × air speed

Air speed (ft./min)	Wet-bulb 85 F	Wet-bulb 88 F	Mean
20	2214	3131	2672
100	2044	2457	2251
300	2032	2218	2125
500	2087	2288	2188
Mean	2094	2524	2309

Standard error for a single mean 32

Temperature × humidity × air speed

Air speed (ft./min)	Dry-bulb 90 F		Dry-bulb 120 F		D.B. × W.B. interaction
	Wet-bulb 85 F	Wet-bulb 88 F	Wet-bulb 85 F	Wet-bulb 88 F	
20	1347	1905	3081	4357	359
100	1086	1366	3022	3548	133
300	956	1113	3108	3324	30
500	846	954	3329	3622	92
Mean	1059	1334	3130	3713	154

Standard error for a single mean 46

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	2565	3315	2940
Resting	1558	1797	1678
Mean	2062	2556	2309

Standard error for a single mean 23

Climate work-clothing interactions

Temperature × air speed × work rate × clothing

Air speed (ft./min)	Dry-bulb 90 F				Dry-bulb 120 F			
	Working		Resting		Working		Resting	
	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls
20	1750	3039	665	1048	3998	4666	2583	3625
100	1481	2238	491	690	3456	4590	2337	2714
300	1292	1925	394	524	3566	4143	2574	2579
500	1162	1601	361	471	4001	4125	3054	2718
Mean	1421	2201	478	683	3755	4381	2637	2909

Standard error for a single mean 65

Temperature × air speed × work rate (working — resting)

Air speed (ft./min)	Dry-bulb 90 F		Dry-bulb 120 F	
	Shorts	Overalls	Shorts	Overalls
20	1085	1991	1415	1041
100	990	1548	1119	1876
300	898	1401	992	1564
500	801	1130	947	1407

Standard error for a single mean 91

Humidity × work rate × clothing

	Wet-bulb 85 F	Wet-bulb 88 F
Shorts working	2396	2735
Shorts resting	1475	1641
Overalls working	2945	3685
Overalls resting	1560	2033

Standard error for a single mean 32

TABLE 22

Series III, Section A. Total sweat loss. Mean values (grams). Illustrating the 'crossing over' effect of shorts and overalls

Dry-bulb temperature 90 F

Wet-bulb (F)	Air speed (ft./min)	Working Shorts	Working Overalls	Resting Shorts	Resting Overalls
85	20	1543	2454	575	818
	100	1311	1918	482	631
	300	1213	1694	428	491
	500	1101	1488	375	418
88	20	1958	3626	756	1280
	100	1652	2559	503	750
	300	1374	2158	361	558
	500	1225	1716	348	527

Dry-bulb temperature 120 F

Wet-bulb (°F)	Air speed (ft./min)	Working Shorts	Working Overalls	Resting Shorts	Resting Overalls
85	20	3327	4041	2091	2864
	100	3262	4151	2261	2335
	300	3542	4009	2549	2332
	500	3872	3808	3039	2595
88	20	4671	5292	3077	4388
	100	3653	5030	2415	3094
	300	3593	4277	2600	2826
	500	4131	4444	3070	2843

Standard error for a single mean 91

TABLE 23

Series III, Section B. Total sweat loss. Mean values (grams) for significant effects

Climate effects

Humidity × air speed

Air speed (ft./min)	Wet-bulb 80 F	Wet-bulb 83°F	Mean
20	1399	1739	1569
100	1504	1495	1500
300	1408	1588	1498
500	1488	1614	1551
Mean	1450	1609	1529

Standard error for a single mean 33

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	1816	2180	1998
Resting	1058	1062	1060
Mean	1437	1621	1529

Standard error for a single mean 47

Climate work-clothing interactions

Air speed × work rate × clothing

Air speed (ft./min)	Working	Resting	Shorts	Overalls
20	2140	997	1344	1793
100	1978	1021	1423	1577
300	1915	1080	1434	1562
500	1959	1142	1548	1554

Humidity × work rate × clothing

	Wet-bulb 80°F	Wet-bulb 83°F
Shorts working	1743	1891
Shorts resting	1045	1072
Overalls working	2008	2353
Overalls resting	1005	1121

Standard error for a single mean 33

TABLE 24

Series III, Section B. Total sweat loss. Mean values (grams). Illustrating the 'crossing over' effect of shorts and overalls

Wet-bulb (°F)	Air speed (ft./min)	Working Shorts	Working Overalls	Resting Shorts	Resting Overalls
80	20	1654	2132	862	947
	100	1829	2112	1092	986
	300	1602	1930	1084	1016
	500	1887	1855	1140	1071
83	20	1928	2847	934	1245
	100	1778	2194	992	1015
	300	1915	2214	1134	1088
	500	1937	2159	1229	1130

Standard error for a single mean 66

TABLE 25

Series III, Section A. Rectal temperature at end of third work period. Mean values (°F) for significant effects

Climate effects

Temperature × air speed

Air speed (ft./min)	Dry-bulb 90°F	Dry-bulb 120°F	Mean
20	99·98	100·92	100·45
100	99·67	100·40	100·04
300	99·63	100·26	99·94
500	99·50	100·20	99·85
Mean	99·70	100·44	100·07

Humidity × air speed

Air speed (ft./min)	Wet-bulb 85°F	Wet-bulb 88°F	Mean
20	100·12	100·78	100·45
100	99·87	100·20	100·04
300	99·84	100·05	99·94
500	99·78	99·92	99·85
Mean	99·90	100·24	100·07

Standard error for a single mean 0·046

Temperature × humidity × air speed

Air speed (ft./min)	Dry-bulb 90°F		Dry-bulb 120°F		D.B. × W.B interaction
	Wet-bulb 85°F	Wet-bulb 88°F	Wet-bulb 85°F	Wet-bulb 88°F	
20	99·83	100·12	100·41	101·43	0·365
100	99·52	99·82	100·22	100·58	0·03
300	99·56	99·70	100·12	100·40	0·07
500	99·48	99·53	100·09	100·30	0·08
Mean	99·60	99·79	100·21	100·68	—

Standard error for a single mean 0·066

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	100·55	101·01	100·78
Resting	99·28	99·43	99·36
Mean	99·92	100·22	100·07

Standard error for a single mean 0·033

Climate work-clothing interactions

Temperature × air speed × work rate × clothing

Air speed (ft./min)	Dry-bulb 90°F				Dry-bulb 120°F			
	Working		Resting		Working		Resting	
	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls
20	100·38	100·92	99·27	99·32	101·37	102·66	99·54	100·12
100	100·21	100·42	98·94	99·11	100·71	101·82	99·53	99·52
300	100·09	100·24	99·05	99·14	100·87	101·06	99·52	99·61
500	99·94	100·07	98·87	99·13	100·86	100·86	99·55	99·50
Mean	100·16	100·41	99·03	99·18	100·95	101·60	59·54	99·69

Standard error for a single mean 0·093

Humidity × work rate × clothing

	Wet-bulb 85°F	Wet-bulb 88°F
Shorts working	100·44	100·66
Shorts resting	99·18	99·38
Overalls working	100·64	101·37
Overalls resting	99·34	99·53

Standard error for a single mean 0·046

TABLE 26

Series III, Section B. Rectal temperature at end of third work period. Mean values (°F) for significant effects

Working subjects	100·21
Resting subjects	99·13
Difference	1·08

Standard error for a single mean 0·028

TABLE 27

Series III, Section A. Rectal temperature at end of fourth (final) work period. Mean values (°F) for significant effects

Climate effects

Temperature × humidity × air speed

Air speed (ft./min)	Dry-bulb 90 F		Dry-bulb 120 F		Mean	D.B. × W.B. interaction
	Wet-bulb 85 F	Wet-bulb 88°F	Wet-bulb 85°F	Wet-bulb 88 F		
20	99·74	99·89	100·30	101·40	100·33	0·48
100	99·39	99·52	100·10	100·38	99·85	0·08
300	99·34	99·60	100·08	100·36	99·85	−0·01
500	99·30	99·22	100·01	100·35	99·72	0·21
Mean	99·44	99·56	100·12	100·62	99·94	

Standard error for a single mean 0·070

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	100·29	100·63	100·46
Resting	99·33	99·49	99·41
Mean	99·81	100·06	99·94

Standard error for a single mean 0·035

Climate work-clothing interactions

Temperature × air speed × work rate × clothing

Air speed (ft./min)	Dry-bulb 90 F				Dry-bulb 120 F			
	Working		Resting		Working		Resting	
	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls	Shorts	Overalls
20	100·12	100·51	99·23	99·41	101·09	102·43	99·71	100·16
100	99·81	99·95	98·91	99·14	100·54	101·34	99·53	99·54
300	99·87	99·82	99·07	99·14	100·64	100·81	99·59	99·84
500	99·57	99·62	98·82	99·05	100·71	100·58	99·81	99·62
Mean	99·84	99·97	99·01	99·19	100·75	101·29	99·66	99·79

Standard error for a single mean 0·099

Humidity × work rate × clothing

	Wet-bulb 85 F	Wet-bulb 88 F
Shorts working	100·18	100·41
Shorts resting	99·26	99·40
Overalls working	100·28	100·98
Overalls resting	99·41	99·57

Standard error for a single mean 0·050

TABLE 28

Series III, Section B. Rectal temperature at end of fourth (final) work period. Mean values (°F) for significant effects

Working subjects	99·95
Resting subjects	99·16
Difference	0·79

Standard error for a single mean 0·037

TABLE 29

Series III, Section A. Standing pulse rate after the third work period. Mean values (beats/min) for significant effects

Climate effects

Temperature × humidity × air speed

Air speed (ft./min)	Dry-bulb 90°F		Dry-bulb 120°F		Mean	D.B. × W.B. interaction
	Wet-bulb 85°F	Wet-bulb 88°F	Wet-bulb 85°F	Wet-bulb 88°F		
20	100	106	122	143	118	8
100	94	100	117	126	109	1
300	89	94	114	124	105	3
500	85	95	118	124	105	−2
Mean	92	99	118	129	109	2

Standard error for a single mean 2·1

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	119	134	127
Resting	90	94	92
Mean	104	114	109

Standard error for a single mean 1·0

Climate work-clothing interactions

Air speed × work rate × clothing

Air speed (ft./min)	Working		Resting	
	Shorts	Overalls	Shorts	Overalls
20	129	150	91	100
100	116	137	88	96
300	114	127	89	91
500	116	122	92	91

Temperature × air speed × clothing

Air speed (ft./min)	Dry-bulb 90°F		Dry-bulb 120°F	
	Shorts	Overalls	Shorts	Overalls
20	98	109	123	142
100	92	102	112	132
300	87	96	116	122
500	87	93	121	120

Standard error for a single mean 2·1

Temperature × humidity × work rate

	Dry-bulb 90°F		Dry-bulb 120°F	
	Wet-bulb 85°F	Wet-bulb 88°F	Wet-bulb 85°F	Wet-bulb 88°F
Working	104	115	137	151
Resting	81	82	99	107

Standard error for a single mean 1·5

TABLE 30

Series III, Section B. Standing pulse rate after the third work period. Mean values (beats/min) for significant effects

Climate effects

Humidity × air speed

Air speed (ft./min)	Wet-bulb 80°F	Wet-bulb 83°F	Mean
20	95	101	98
100	88	99	94
300	96	98	97
500	96	92	94
Mean	94	98	96

Standard error for a single mean 1·7

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	103	112	107
Resting	83	85	84
Mean	93	98	96

Standard error for a single mean 1·2

Climate work-clothing interactions

Air speed × work rate

Air speed (ft./min)	Working	Resting
20	111	85
100	109	79
300	106	88
500	104	85

Standard error for a single mean 1·7

TABLE 31

Series III, Section A. Standing pulse rate after the fourth (final) work period. Mean values (beats/min) for significant effects

Climate effects

Temperature × humidity × air speed

Air speed (ft./min)	Dry-bulb 90° F Wet-bulb 85° F	Dry-bulb 90° F Wet-bulb 88° F	Dry-bulb 120° F Wet-bulb 85° F	Dry-bulb 120° F Wet-bulb 88° F	Mean	D.B. × W.B. interaction
20	101	107	124	148	120	9
100	89	96	118	128	108	2
300	86	91	115	119	103	0
500	82	89	119	128	104	0
Mean	90	96	119	131	109	3

Standard error for a single mean 1·8

Work-clothing effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	119	133	126
Resting	90	94	92
Mean	104	114	109

Standard error for a single mean 0·9

Climate work-clothing interactions

Temperature × humidity × work rate

	Dry-bulb 90° F Wet-bulb 85° F	Dry-bulb 90° F Wet-bulb 88° F	Dry-bulb 120° F Wet-bulb 85° F	Dry-bulb 120° F Wet-bulb 88° F
Working	101	112	139	151
Resting	78	79	99	110

Standard error for a single mean 1·3

Temperature × air speed × clothing

Air speed (ft./min)	Dry-bulb 90° F Shorts	Dry-bulb 90° F Overalls	Dry-bulb 120° F Shorts	Dry-bulb 120° F Overalls
20	98	110	125	147
100	89	96	114	132
300	85	92	114	121
500	84	88	125	122
Mean	89	96	120	130

Standard error for a single mean 1·8

Air speed × work rate

Air speed (ft./min)	Working	Resting
20	140	100
100	126	90
300	119	88
500	119	90

Standard error for a single mean 1·3

TABLE 32

Series III, Section B. Standing pulse rate after the fourth (final) work period. Mean values (beats/min) for significant effects

Work rate × clothing

	Shorts	Overalls	Mean
Working	102	110	106
Resting	84	82	83
Mean	93	96	

Standard error for a single mean 0·8

TABLE 33

Comparison of the mean differences between the observed sweat losses and the P4SR values for the environments used in Series I, II and III

Series	Observed sweat loss P4SR (litres)	Degrees of Freedom	'*t*' value
I	0·026	63	0·59 N.S.
II (pre-acclim.)	0·332	79	6·83***
II (post-acclim.)	0·363	47	5·58***
III	−0·056	95	2·06*

* Significant at 5% level
*** Significant at 0·1% level
N.S. Not significant

TABLE 34

Total sweat loss (grams). Comparison of the observed (O) and expected (E) differences between the effects of shorts and overalls, and between the effects of working and resting in Series I. (Expected differences calculated from the equation relating the P4SR Index and the observed sweat losses)

Air speed (ft./min)		Dry-bulb 90°F				Dry-bulb 120°F			
		Wet-bulb 80°F		Wet-bulb 85°F		Wet-bulb 80°F		Wet-bulb 85°F	
		Shorts − overalls	Work − rest	Shorts − overalls	Work − rest	Shorts − overalls	Work − rest	Shorts − overalls	Work − rest
20	O	−248	1137	−206	1515	−427	1558	−338	1635
	E	−416	847	−523	1052	−440	930	−557	1203
	O − E	168	290	317	463	13	630	239	432
100	O	7	1015	−305	1180	269	1244	−388	1582
	E	−392	793	−445	924	−401	822	−475	964
	O − E	399	222	140	256	670	422	87	618
300	O	−152	689	−110	1124	267	1148	266	1051
	E	−401	792	−450	900	−401	812	−470	969
	O − E	249	−107	340	224	668	336	736	82
500	O	−115	927	−103	993	664	1105	333	1475
	E	−392	783	−440	890	−401	803	−460	938
	O − E	277	144	337	103	1065	302	793	518

TABLE 35

Analysis of variance of the deviations of the observed values for the total (four-hour) sweat loss from the predicted (P4SR) values in Series II and Series III. Significant main effects and first-order interactions only

Source of variation	Series II		Series III	
	Part 1	Part 2	Section A	Section B
Dry-bulb temperature	*	–	–	–
Wet-bulb temperature	–	–	–	**
Metabolic rate	**	*	**	**
Clothing	*	–	**	**
Dry- wet-bulb temperature ...	–	–	**	–
Wet-bulb air speed	–	–	–	*
Air speed metabolic rate ...	–	–	**	*
Air speed clothing ...	–	–	*	**

* Significant at 5% level
** Significant at 1% level

TABLE 36

Total sweat loss (grams). Comparison of the observed values (O) with the predicted (P4SR) values (E) at all climate work-clothing combinations at dry-bulb temperatures 90°F and 120°F used in Series I, II (Part I) and III

Air speed (ft./min.)		Shorts		Overalls		Shorts		Overalls	
		Work	Rest	Work	Rest	Work	Rest	Work	Rest
		Wet-bulb 80°F. Series I				Wet-bulb 83°F. Series II			
		Dry-bulb temperature 90°F							
20	O	1523	350	1734	634	1602	704	2617	887
	E	1290	400	1920	680	1420	460	2190	760
	O − E	233	−50	−186	−46	182	244	427	127
100	O	1349	509	1517	328	1483	397	1888	973
	E	1140	310	1750	570	1160	290	1860	560
	O − E	209	199	−233	−242	323	107	28	413
300	O	1268	560	1396	735	1558	541	1640	587
	E	1100	260	1710	530	1110	240	1770	510
	O − E	168	300	−314	205	448	301	−130	77
500	O	1197	222	1264	385	1405	575	1717	512
	E	960	135	1570	395	1040	190	1690	450
	O − E	237	87	−306	−10	355	385	27	62
		Dry-bulb temperature 120°F							
20/40	O	3165	2144	4128	2034	3910	2210	5880	3180
	E	3120	2140	3780	2430	3260	2210	4150	2570
	O − E	45	4	348	−396	650	0	1730	610
100	O	3356	2134	3109	1843	3690	2480	4130	2180
	E	3030	2170	3650	2440	3210	2330	3990	2610
	O − E	326	−36	−541	−597	470	150	140	−430
300	O	3600	2809	3690	2246	4270	2830	3920	2290
	E	3400	2540	4010	2810	3490	2600	4160	2880
	O − E	200	269	−320	−564	780	230	−240	−590
500	O	4200	3094	3535	2431	4290	2900	4110	2470
	E	3610	2760	4230	3030	3620	2750	4300	3030
	O − E	590	334	−695	−599	670	150	−190	−560
		Wet-bulb 85°F. Series I				Wet-bulb 85°F. Series III			
		Dry-bulb temperature 90°F							
20	O	2058	638	2358	749	1543	575	2454	818
	E	1510	460	2320	780	1650	540	2610	880
	O − E	548	178	38	−31	−107	−35	−156	−62
100	O	1648	409	1894	773	1311	482	1918	631
	E	1280	340	1990	620	1300	360	2040	650
	O − E	368	69	−96	153	11	122	−122	−19
300	O	1342	357	1590	328	1213	428	1694	491
	E	1180	260	1880	540	1190	260	1910	550
	O − E	162	97	−290	−212	23	168	−216	−59
500	O	1199	384	1480	309	1101	375	1488	418
	E	1120	210	1810	490	1060	160	1750	450
	O − E	79	174	−330	−181	41	215	−262	−32
		Dry-bulb temperature 120°F							
20/40	O	4327	2211	4183	3030	3327	2091	4041	2864
	E	3460	2260	4380	2600	3730	2420	4760	2770
	O − E	867	−49	−197	430	−403	−329	−719	94
100	O	3113	2107	4077	1919	3262	2261	4151	2335
	E	3210	2250	3970	2530	3310	2320	4060	2610
	O − E	−97	−143	107	−611	−48	59	91	−275
300	O	3543	2587	3372	2226	3542	2549	4009	2332
	E	3560	2570	4290	2860	3540	2550	4270	2830
	O − E	−17	17	−918	−634	2	1	−261	−498
500	O	4367	3093	4217	2577	3872	3039	3808	2595
	E	3730	2770	4440	3060	3710	2740	4390	3020
	O − E	637	323	−223	−483	162	299	−582	−425

(continued on page 239)

TABLE 36—(*continued*)

Total sweat loss (gram). Comparison of the observed values (O) *with the predicted (P4SR) values (E) at all climate work-clothing combinations at dry-bulb temperatures* 90°*F and* 120°*F used in Series I, II (Part I) and III*

Air speed (ft./min)		Shorts		Overalls		Shorts		Overalls	
		Work	Rest	Work	Rest	Work	Rest	Work	Rest
		Wet-bulb 88°F. Series II				Wet-bulb 88°F. Series III			
		Dry-bulb temperature 90°F							
20	O	3435	803	4267	1411	1958	756	3626	1280
	E	2410	670	4120	1120	2620	740	4430	1180
	O − E	1025	133	147	291	−662	16	−804	100
100	O	2438	569	3560	876	1652	503	2559	750
	E	1510	410	2410	740	1570	460	2600	800
	O − E	928	159	1150	136	82	43	−41	−50
300	O	1672	453	2327	748	1374	361	2158	558
	E	1370	300	2230	630	1410	330	2270	670
	O − E	302	153	97	118	−36	31	−112	−112
500	O	1455	377	2693	562	1225	348	1716	527
	E	1260	240	2060	550	1250	230	1040	540
	O − E	195	137	633	12	−25	118	−324	−13
		Dry-bulb temperature 120°F							
20/40	O	6050	3330	6010	4180	4671	3077	5292	4388
	E	4510	2670	5730	3220	4620	2770	5960	3390
	O − E	1540	660	280	960	51	307	−668	998
100	O	5060	3040	4880	3340	3652	2415	5030	3094
	E	3670	2460	4550	2870	3600	2420	4450	2780
	O − E	1390	580	330	470	52	−5	580	314
300	O	4000	2870	5270	3330	3593	2600	4277	2826
	E	3840	2710	4690	3030	3780	2640	4600	3000
	O − E	160	160	580	300	−187	−40	−323	−174
500	O	4160	3390	4630	3090	4131	3070	4444	2843
	E	3970	2850	4790	3200	3880	2780	4690	3120
	O − E	190	540	−160	−110	251	290	−246	−277

TABLE 37

Series III. Total sweat loss (grams). Comparison of the observed values (O) *with the predicted (P4SR) values* (E) *at all wet-bulb work-clothing combinations at dry-bulb temperature* 100°*F*

Air speed (ft./min)		Wet-bulb 80°F				Wet-bulb 83°F			
		Shorts		Overalls		Shorts		Overalls	
		Work	Rest	Work	Rest	Work	Rest	Work	Rest
40	O	1654	862	2132	947	1928	934	2847	1245
	E	1780	890	2410	1160	1970	940	2740	1230
	O − E	−126	−28	−278	−213	−42	−6	107	15
100	O	1829	1092	2112	986	1778	992	2194	1015
	E	1690	860	2290	1120	1730	870	2390	1140
	O − E	139	232	−178	−134	48	122	−196	125
300	O	1602	1084	1930	1016	1915	1134	2214	1088
	E	1730	890	2320	1140	1790	930	2480	1190
	O − E	−128	194	−390	−124	125	204	−266	−102
500	O	1887	1140	1855	1071	1937	1229	2159	1130
	E	1720	880	2340	1160	1770	910	2440	1170
	O − E	167	260	−485	−89	167	319	−281	40

TABLE 38

Total sweat loss (grams). Comparison of values in Series III (S) *with corresponding London results* (L)

The top figure of each group is the Series III mean of six subjects. The middle figure is the London mean of two subjects, except where bracketed numbers indicate otherwise

Air speed (ft./min)		Shorts		Overalls		Shorts		Overalls	
		Work	Rest	Work	Rest	Work	Rest	Work	Rest
		Dry-bulb 90 F, wet-bulb 88°F				*Dry-bulb 120 F, wet-bulb 88 F*			
20	S	1958	756	3626	1280	4671	3077	5292	4388
	L	2879	772	3353	1604	4934	2779	—	4173
	S − L	−921	−16	273	−324	−263	298	—	215
100	S	1652	503	2559	750	3653	2415	5030	3094
	L	1661	625	2505	645	3958	2610(1)	4957	3518
	S − L	−9	−122	54	105	−305	−195	73	−424
300	S	1374	361	2158	558	3593	2600	4277	2826
	L	1276	318	1925	340	4218	2748	3988	2880
	S − L	98	43	233	218	−625	−148	289	−54
500	S	1225	348	1716	527	4131	3070	4444	2843
	L	1043	263	1854	365	4718	3205	4155	3318
	S − L	182	85	−138	162	−587	−135	289	475
		Dry-bulb 100 F, wet-bulb 83 F				*Dry-bulb 120°F, wet-bulb 85 F**			
20	S	1928	934	2847	1245	3327	2091	4041	2864
	L	1906	962	2527	1115	3516(4)	2507(3)	4928(19)	3012(2)
	S − L	22	−28	320	130	−189	−416	−887	−148
100	S	1778	992	2194	1015	3262	2261	4151	2335
	L	1708	1121	2387	1227	3863(1)	2599(2)	4665(2)	—
	S − L	70	−129	−193	−212	−601	−338	−514	—
300	S	1915	1134	2214	1088	—	—	—	—
	L	2121(1)	1058	2662(1)	1128	—	—	—	—
	S − L	−206	76	−448	−40	—	—	—	—
500	S	1937	1229	2159	1130	3872	3039	3808	2595
	L	2016	1123	2200	1206	3988(2)	3053(5)	4718(8)	—
	S − L	−79	106	−41	−76	−116	−14	−910	—

* The London results at this climate were not part of the main experiments and are based on the numbers of subjects given in brackets.

TABLE 39

Series III. Final rectal temperature (°F). Comparison of the observed values (O) *with those expected from the value of the P4SR Index* (E)

Dry-bulb (°F)	Air speed (ft./min)		Shorts		Overalls		Shorts		Overalls	
			Work	Rest	Work	Rest	Work	Rest	Work	Rest
			Wet-bulb 85° F				*Wet-bulb 88° F*			
90	20	O	99·9	99·2	100·4	99·4	100·3	99·2	100·6	99·4
		E	99·6	99·0	100·1	99·2	100·1	99·1	101·0	99·3
		O − E	0·3	0·2	0·3	0·2	0·2	0·1	−0·4	0·1
	100	O	99·8	98·8	99·8	99·2	99·9	99·0	100·1	99·1
		E	99·4	98·9	99·8	99·1	99·5	99·0	100·1	99·1
		O − E	0·4	−0·1	0·0	0·1	0·4	0·0	0·0	0·0
	300	O	99·8	98·8	99·6	99·2	99·9	99·4	100·0	99·1
		E	99·3	98·9	99·7	99·0	99·5	98·9	99·9	99·1
		O − E	0·5	−0·1	−0·1	0·2	0·4	0·5	0·1	0·0
	500	O	99·8	98·7	99·5	99·2	99·3	99·0	99·8	98·9
		E	99·3	98·8	99·6	99·0	99·4	98·9	99·8	99·0
		O − E	0·5	−0·1	−0·1	0·2	−0·1	0·1	0·0	−0·1
			Wet-bulb 80° F				*Wet-bulb 83° F*			
100	20	O	99·8	99·0	100·0	99·2	99·8	99·3	100·2	99·3
		E	99·6	99·2	100·0	99·3	99·7	99·2	100·1	99·4
		O − E	0·2	−0·2	0·0	−0·1	0·1	0·1	0·1	−0·1
	100	O	99·9	99·0	100·0	99·1	99·9	99·4	99·9	98·9
		E	99·6	99·2	99·9	99·3	99·6	99·2	100·0	99·3
		O − E	0·3	−0·2	0·1	−0·2	0·3	0·2	−0·1	−0·4
	300	O	100·6	99·1	99·8	99·2	99·7	99·6	100·0	99·2
		E	99·6	99·2	99·9	99·3	99·7	99·2	100·0	99·3
		O − E	1·0	−0·1	−0·1	−0·1	0·0	0·4	0·0	−0·1
	500	O	99·9	98·8	99·8	99·3	99·8	99·2	99·9	99·1
		E	99·6	99·2	99·9	99·3	99·6	99·2	100·0	99·3
		O − E	0·3	−0·4	−0·1	0·0	0·2	0·0	−0·1	−0·2
			Wet-bulb 85° F				*Wet-bulb 88° F*			
120	20	O	100·6	99·6	101·3	99·7	101·6	99·8	103·5	100·6
		E	100·6	100·0	101·2	100·2	101·1	100·2	101·8	100·5
		O − E	0·0	−0·4	0·1	−0·5	0·5	−0·4	1·7	0·1
	100	O	100·5	99·6	100·9	99·4	100·6	99·5	101·8	99·7
		E	100·4	99·9	100·8	100·1	100·6	100·0	101·0	100·2
		O − E	0·1	−0·3	0·1	−0·7	0·0	−0·5	0·8	−0·5
	300	O	100·5	99·7	100·4	99·7	100·8	99·5	101·2	100·0
		E	100·5	100·0	100·9	100·2	100·7	100·1	101·1	100·3
		O − E	0·0	−0·3	−0·5	−0·5	0·1	−0·6	0·1	−0·3
	500	O	100·4	99·8	100·3	99·5	101·0	99·8	100·9	99·8
		E	100·6	100·1	101·0	100·3	100·7	100·2	101·1	100·3
		O − E	−0·2	−0·3	−0·7	−0·8	0·3	−0·4	−0·2	−0·5

Note: The expected value for the rectal temperature (E) has been calculated from the regression equation $E = 98{\cdot}74 + 0{\cdot}5099x$ where x is the value of the P4SR Index.

TABLE 40

Series III. Final standing pulse rate (beats/min). Comparison of the observed values (O) *with those expected from the value of the P4SR Index* (E)

Dry-bulb (°F)	Air-speed (ft./min)		Shorts		Overalls		Shorts		Overalls	
			Work	Rest	Work	Rest	Work	Rest	Work	Rest
			Wet-bulb 85°F				*Wet-bulb 88°F*			
90	20	O	102	90	131	82	119	83	141	86
		E	96	77	113	83	113	80	145	88
		O − E	6	13	18	−1	6	3	−4	−2
	100	O	96	79	104	78	105	77	119	81
		E	90	73	103	79	95	75	113	81
		O − E	6	6	1	−1	10	2	6	0
	300	O	91	73	104	77	97	80	111	77
		E	88	72	100	77	92	73	107	79
		O − E	3	1	4	0	5	7	4	−2
	500	O	88	72	91	76	99	74	107	77
		E	86	70	98	75	89	71	103	77
		O − E	2	2	−7	1	10	3	4	0
			Wet-bulb 80°F				*Wet-bulb 83°F*			
100	20	O	97	83	111	83	106	84	119	91
		E	98	83	109	87	102	84	115	89
		O − E	−1	0	2	−4	4	0	4	2
	100	O	97	80	108	80	109	82	113	82
		E	97	82	107	87	97	82	109	87
		O − E	0	−2	1	−7	12	0	4	−5
	300	O	108	88	109	77	91	88	109	81
		E	97	83	108	87	99	83	111	88
		O − E	11	5	1	−10	−8	5	−2	−7
	500	O	103	86	104	83	103	82	103	80
		E	97	83	108	87	98	83	110	88
		O − E	6	3	−4	−4	5	−1	−7	−8
			Wet-bulb 85°F				*Wet-bulb 88°F*			
120	20	O	134	96	154	113	159	112	184	135
		E	132	109	150	116	148	116	171	126
		O − E	2	−13	4	−3	11	−4	13	9
	100	O	127	89	155	100	136	103	163	112
		E	125	108	138	113	130	109	145	116
		O − E	2	−19	17	−13	6	−6	18	−4
	300	O	129	89	140	102	135	101	140	101
		E	129	112	142	117	133	113	148	120
		O − E	0	−23	−2	−15	2	−12	−8	−19
	500	O	134	102	138	103	148	115	142	104
		E	132	115	144	120	135	116	149	122
		O − E	2	−13	−6	−17	13	−1	7	−18

Note: The expected value for the standing pulse rate (E) has been calculated from the regression equation $E = 67{\cdot}2 + 17{\cdot}47x$ where x is the value of the P4SR Index.

TABLE 41

Conditions found to be intolerable in Series II

Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Air speed (ft./min)	No. of subjects who failed to complete experiment*					
			Pre-acclimatization			Post-acclimatization		
			Shorts working	Overalls working	Total	Shorts working	Overalls working	Total
120	88	20	3	3	6	2	3	5
		100	0	3	3	1	1	2
		300	0	0	0	0	3	3
		500	0	1	1	—	—	—
120	85	20	0	2	2	—	—	—
120	83	20	0	2	2	0	0	0
		100	1	1	2	0	0	0
		300	1	0	1	0	0	0
		Total	5	12	17	3	7	10

* One subject also failed unexpectedly at dry-bulb 90°F, wet-bulb 88°F air speed 20 ft./min in the post-acclimatization period.

TABLE 42

The P4SR indices of the environments at dry-bulb temperature 120°F in Series II in which one or more of the subjects failed to complete the four-hour experiments (see Table 41)

Environment		P4SR Index	
Wet-bulb temperature (°F)	Air speed (ft./min)	Shorts working	Overalls working
88	20	5·20	6·63
	100	3·83	4·73
	300	4·00	4·85
	500	4·19	5·04
85	20	4·31	5·39
83	20	3·85	4·79
	100	3·33	3·99
	300	3·57	4·28

Tables to Chapter 5

TABLE 43

Series IV. Sweat losses in the uniformity trial

Subject	Weight (kg)	Surface area (m^2)	Sweat loss (g) Total	Per kg body weight	Per m^2 body surface
1	60·150	1·702	1903	31·64	1118
2	62·947	1·746	2020	32·09	1157
3	58·529	1·660	1965	33·67	1184
4	56·215	1·620	2003	35·63	1236
5	66·872	1·788	2135	31·93	1194
6	62·965	1·739	1965	31·21	1130
7	64·717	1·749	2002	30·94	1145
8	64·287	1·760	2225	34·61	1264
9	73·210	1·891	2305	31·48	1219
10	58·202	1·653	1867	32·08	1129
11	71·845	1·876	2385	33·20	1271
12	65·825	1·800	1990	30·23	1106
13	62·035	1·718	2365	38·12	1377
14	73·520	1·872	2410	32·78	1287
15	61·150	1·739	1990	32·54	1144
16	70·425	1·804	2528	35·90	1401
17	60·272	1·696	1832	30·40	1080
18	60·380	1·740	2186	36·20	1256
19	65·720	1·790	2111	32·12	1179
20	67·934	1·766	2422	35·65	1371
21	70·425	1·845	2153	30·57	1167
22	62·605	1·723	2196	35·08	1275
23	62·532	1·740	2082	33·29	1197
24	61·064	1·723	1858	30·43	1079
25	85·630	2·031	2710	31·65	1334
26	59·330	1·690	2085	35·14	1234
27	71·600	1·897	2340	32·68	1234
28	70·050	1·880	2292	32·72	1219
29	71·749	1·882	2274	31·69	1208
30	61·482	1·705	2142	34·84	1256
31	67·860	1·777	2480	36·55	1400
32	66·885	1·731	2585	38·64	1493

Total sweat (g)	Range 1832 – 2710 Mean 2181	S.D. 223
Sweat/kg (g)	Range 30·23 – 38·64 Mean 33·30	S.D. 2·34
Sweat/m^2 (g)	Range 1080 – 1493 Mean 1229·5	S.D. 101

TABLE 44

Series IV. Sweat losses and P4SR values in the factorial experiment

D_1 and D_2 = dry-bulb temperatures 90 and 120°F; A_1 and A_2 = air speeds 20 and 300 ft./min
W_1 and W_2 = wet-bulb temperatures 80 and 85°F; P_1 and P_2 = sitting and working in shorts

Environment	Subject	Sweat loss (g)				P4SR Index
		Per kg body weight	Per m² body surface	Total	Corrected total*	
D_1 W_1 A_1 P_1	1	7·6	268	455	614	0·420
	2	8·0	287	501	593	
P_2	3	23·0	811	1347	1471	1·238
	4	29·7	1032	1672	1774	
A_2 P_1	5	7·4	275	490	517	0·180
	6	7·2	261	455	579	
P_2	7	18·0	664	1161	1264	0·948
	8	20·3	739	1295	1270	
W_2 A_1 P_1	9	8·4	325	615	544	0·530
	10	9·7	340	560	740	
P_2	11	28·9	1108	2080	1964	1·528
	12	27·8	1014	1820	1929	
A_2 P_1	13	5·1	183	310	205	0·190
	14	4·4	171	320	189	
P_2	15	20·7	724	1250	1359	1·018
	16	21·6	843	1519	1321	
D_2 W_1 A_1 P_1	17	26·4	940	1595	1795	2·380
	18	30·2	1041	1801	1798	
P_2	19	47·4	1731	3085	3125	3·348
	20	49·2	1900	3367	3229	
A_2 P_1	21	42·8	1633	3015	3031	2·680
	22	51·7	1859	3185	3177	
P_2	23	61·7	2209	3845	3902	3·458
	24	59·1	2105	3595	3780	
W_2 A_1 P_1	25	26·9	1140	2320	2018	2·500
	26	32·9	1160	1970	2025	
P_2	27	55·2	2066	3905	3814	3·698
	28	52·2	1937	3640	3577	
A_2 P_1	29	49·3	1872	3520	3467	2·880
	30	52·0	1874	3200	3223	
P_2	31	66·4	2520	4470	4299	3·908
	32	65·9	2540	4415	4184	

* Corrected for differences in the uniformity trial.

TABLE 45

Series IV. Total sweat loss. Mean values (grams) corrected for differences between subjects in the uniformity trial

D_1 and D_2 = dry-bulb temperatures 90 and 120°F; A_1 and A_2 = air speeds 20 and 300 ft./min
W_1 and W_2 = wet-bulb temperatures 80 and 85°F; P_1 and P_2 = sitting and working in shorts

Direct effects

D_1	1021	W_1	1995	A_1	1938	P_1	1532
D_2	3153	W_2	2179	A_2	2235	P_2	2641

Standard error for a single mean 26

First order interactions

	W_1	W_2
D_1	1010	1031
D_2	2980	3326

	A_1	A_2
D_1	1204	838
D_2	2673	3633

	P_1	P_2
D_1	498	1544
D_2	2567	3739

	W_1	W_2
P_1	1513	1551
P_2	2477	2806

	A_1	A_2
P_1	1266	1799
P_2	2610	2672

	W_1	W_2
A_1	1800	2076
A_2	2190	2281

Standard error for a single mean 37

TABLE 46

Series IV. Rectal temperature (°F) during the uniformity trial

Time	Mean	Standard error
Before entry	96·64	0·062
End of Work I	100·89	0·064
End of Rest I	100·25	0·078
End of Work II	100·76	0·071
End of Rest II	100·07	0·070
End of Work III	100·53	0·064
Mid Rest III	99·69	0·063
End of Rest III	99·46	0·060
End of Work IV	100·22	0·070

TABLE 47

Series IV. Final rectal temperature. Mean values (°F) for significant effects

D_1 and D_2 = dry-bulb temperatures 90 and 120°F; A_1 and A_2 = air speeds 20 and 300 ft./min
W_1 and W_2 = wet-bulb temperatures 80 and 85°F; P_1 and P_2 = sitting and working in shorts

Direct effects

D_1	99·1	P_1	99·1
D_2	100·4	P_2	100·4

Standard error for a single mean 0·094

Interactions

	D_1	D_2	W_1	W_2
A_1	99·2	100·1	99·3	100·0
A_2	98·9	100·7	99·8	99·8

Standard error for a single mean 0·132

TABLE 48

Series IV. Standing pulse rate (beats/min) during the uniformity trial

Time	Mean	Standard error
Before entry	87·4	2·8
End of Work I	117·6	3·2
End of Rest I	87·6	3·0
End of Work II	108·0	3·6
End of Rest II	84·4	2·6
End of Work III	104·8	3·2
Mid Rest III	82·6	2·6
End of Rest III	83·0	2·4
End of Work IV	104 4	2·8

TABLE 49

Series IV. Final standing pulse rate. Mean values (beats/min), corrected for differences between subjects in the uniformity trial, for significant effects

D_1 and D_2 = dry-bulb temperatures 90 and 120°F; A_1 and A_2 = air speeds 20 and 300 ft./min
W_1 and W_2 = wet-bulb temperatures 80 and 85°F; P_1 and P_2 = sitting and working in shorts

Direct effects

D_1	77	W_1	93	P_1	81
D_2	119	W_2	103	P_2	115

Standard error for a single mean 2·7

Interactions

	A_1	A_2		P_1	P_2		P_1	P_2
D_1	79	74	D_1	67	86	W_1	81	105
D_2	113	125	D_2	94	143	W_2	81	125

Standard error for a single mean 3·8

TABLE 50

Series IV. Total sweat loss (grams). Comparison of the observed values (O) and the predicted (P4SR) values (E) for significant effects

D_1 and D_2 = dry-bulb temperatures 90 and 120°F
A_1 and A_2 = air speeds 20 and 300 ft./min
P_1 and P_2 = sitting and working in shorts

Direct effects

	D_1	D_2	A_1	A_2	P_1	P_2
O	991	3183	1921	2253	1520	2654
E	921	3254	2111	2064	1630	2546
O − E	70	−71	−190	189	−110	108

Standard error for a single mean 37·8

First order interactions

		D_1	D_2		A_1	A_2
O	A_1	1131	2710	P_1	1227	1812
E		1092	3130		1617	1642
O − E		39	−420		−390	170
O	A_2	850	3656	P_2	2615	2694
E		750	3378		2605	2486
O − E		100	278		10	208

Standard error for a single mean 54

TABLE 51

Sweat loss (litres). Comparison of the observed values in Series IV with the predicted (P4SR) values, and with the observed values for the same environmental conditions in Series I and III

Air speed (ft./min)	Work – clothing	Wet-bulb temperature 80°F				Wet-bulb temperature 85°F			
		Ser. I*	Ser. III	Ser. IV*	P4SR	Ser. I*	Ser. III	Ser. IV*	P4SR
		Dry-bulb temperature 90°F							
20	Shorts working	1·523	—	1·623	1·238	2·058	1·543	1·947	1·528
	Shorts resting	0·350	—	0·604	0·420	0·638	0·515	0·642	0·530
300	Shorts working	1·268	—	1·267	0·948	1·342	1·213	1·340	1·018
	Shorts resting	0·560	—	0·548	0·180	0·357	0·428	0·197	0·190
	Mean	0·925	—	1·010	0·697	1·099	0·940	1·032	0·817
		Dry-bulb temperature 120°F							
20	Shorts working	3·165	—	3·177	3·348	4·327	3·327	3·696	3·698
	Shorts resting	2·144	—	1·797	2·380	2·211	2·091	2·022	2·500
300	Shorts working	3·600	—	3·841	3·458	3·543	3·542	4·242	3·908
	Shorts resting	2·809	—	3·104	2·680	2·587	2·549	3·345	2·880
	Mean	2·930	—	2·980	2·967	3·167	2·877	3·326	3·247

* Corrected values.

TABLE 52

Rectal temperature (°F). Comparison of the values in Series IV with those for the same environmental conditions in Series I and III

Air speed (ft./min)	Work – clothing	Wet-bulb temperature 80°F			Wet-bulb temperature 85°F		
		Ser. I	Ser. III	Ser. IV	Ser. I	Ser. III	Ser. IV
		Dry-bulb temperature 90°F					
20	Shorts working	99·9	—	99·3	99·9	99·9	100·0
	Shorts resting	99·1	—	98·6	99·2	99·2	98·9
300	Shorts working	100·0	—	99·6	99·4	99·8	99·5
	Shorts resting	99·1	—	98·2	99·0	98·8	98·4
	Mean	99·6	—	98·9	99·4	99·4	99·2
		Dry-bulb temperature 120°F					
20	Shorts working	100·7	—	100·3	101·5	100·6	101·5
	Shorts resting	99·2	—	99·2	99·8	99·6	99·4
300	Shorts working	100·2	—	101·4	101·3	100·5	101·4
	Shorts resting	99·8	—	100·2	99·6	99·7	99·8
	Mean	100·0	—	100·3	100·6	100·1	100·5

TABLE 53

Pulse rate (beats/min). Comparison of the values in Series IV with those for the same environmental conditions in Series I and III

Air speed (ft./min)	Work clothing	Wet-bulb temperature 80 F			Wet-bulb temperature 85 F		
		Ser. I	Ser. III	Ser. IV	Ser. I	Ser. III	Ser. IV
				Dry-bulb temperature 90°F			
20	Shorts working	108	—	78	117	102	103
	Shorts resting	95	—	72	96	90	64
300	Shorts working	105	—	77	96	91	88
	Shorts resting	80	—	62	90	73	71
	Mean	97	—	72	100	89	82
				Dry-bulb temperature 120 F			
20	Shorts working	133	—	124	149	134	150
	Shorts resting	103	—	91	99	96	86
300	Shorts working	127	—	140	156	129	160
	Shorts resting	105	—	100	112	89	102
	Mean	117	—	114	129	112	125

TABLE 54

Series IV. Sweat rates (grams/min) of sitting men during the periods between weighings

D_1 and D_2 = dry-bulb temperatures 90 and 120°F
W_1 and W_2 = wet-bulb temperatures 80 and 85°F
A_1 and A_2 = air speeds 20 and 300 ft./min

Environment	Subject	Intervals between weighings							
		1 (45 min)↓	2 (20 min)	3 (40 min)↓	4 (20 min)	5 (40 min)↓	6 (25 min)	7 (25 min)	8 (30 min)
D_1 W_1 A_1	1	1·2	2·5	2·3	2·7	1·3	2·4	1·4	2·0
	2	2·3	2·0	2·9	1·3	1·6	1·7	1·5	2·0
A_2	5	2·0	2·5	2·1	1·5	2·5	1·4	1·6	2·0
	6	1·2	1·8	2·0	2·8	2·8	1·2	2·2	1·2
W_2 A_1	9	1·3	3·0	2·4	3·3	2·8	3·6	2·4	2·5
	10	1·4	3·5	2·5	3·0	2·0	2·8	2·6	1·7
A_2	13	1·0	2·0	1·3	2·5	0·9	1·4	1·6	0·5
	14	1·6	1·0	1·5	2·3	1·3	1·2	1·6	0·3
D_2 W_1 A_1	17	6·4	8·3	6·0	6·8	6·1	7·3	6·6	5·8
	18	7·3	8·5	7·3	8·5	6·5	8·2	7·1	6·6
A_2	21	12·3	13·0	12·8	14·3	11·8	11·9	11·4	11·7
	22	11·9	15·1	12·4	11·9	12·2	14·0	14·8	13·7
W_2 A_1	25	6·9	13·8	10·1	12·0	9·8	9·6	8·8	8·0
	26	8·0	11·3	8·4	9·8	7·5	7·4	6·6	6·8
A_2	29	13·6	14·5	15·0	15·5	15·8	13·6	13·8	13·2
	30	10·7	14·3	12·6	14·3	12·9	15·6	13·6	13·3

The arrows (↓) indicate the points at which drinks were given

TABLE 55

Series IV. Analysis of variance of sweat loss in the uniformity trial

'D', 'W', 'A' and 'P' refer to the environmental conditions in which the subjects performed the experiment proper

Source of variation	Degrees of freedom	Sum of squares ($\times 10^{-3}$)	
'D'	1	89	N.S.
'W'	1	426	**
'A'	1	30	N.S.
'P'	1	16	N.S.
'D × W'	1	6	N.S.
'D × A'	1	60	N.S.
'D × P'	1	7	N.S.
'W × A'	1	12	N.S.
'W × P'	1	1	N.S.
'A × P'	1	8	N.S.
Residual	21	934	(M.S. = 44·5)
Total	31	1,589	

** Significant at 1% level
N.S. Not significant

TABLE 56

Series IV. Relation of body weight to amount of sweat lost in the uniformity trial

D_1 and D_2 = dry-bulb temperatures 90 and 120°F; W_1 and W_2 = wet-bulb temperatures 80 and 85°F

Treatment		Subjects	Mean body weight (kg)	Sweat loss (g)	Sweat loss/kg body weight (g)
D_1	W_1	1–8	62·1	2027	33
	W_2	9–16	67·0	2230	33
D_2	W_1	17–24	63·9	2105	33
	W_2	25–32	69·3	2364	35
W_1		1– 8 & 17–24	63·0	2066	33
W_2		9–16 & 25–32	68·2	2297	34

Tables to Chapter 6

TABLE 57

Series V. Summary of analyses of variance of sweat loss per kilogram body weight. Significant effects only

D = dry-bulb temperature; H = humidity; A = air speed; R = radiant heat

Source of variation	Significance	
	At A_1 (100 ft./min)	At A_2 (350 ft./min)
D	***	***
H	**	*
D × H	N.S.	*
R	***	***
R × D	**	N.S.
R × D × H	*	N.S.

*** Significant at the 0·1% level
** Significant at the 1% level
* Significant at the 5% level
N.S. Not significant

TABLE 58

Series V. Sweat loss. Mean values (grams per kilogram body weight)

D_1 = air temperature, lower level (90°F); D_2 = upper level (110°F)
H_1 = humidity, lower level (16·5 mm Hg); H_2 = upper level (27·0 mm Hg)
R_1 = added radiant heat, lower level (nil); R_2 = upper level
(at A_1, approx. 21°F)
(at A_2, approx. 16°F)

	D_1H_1	D_1H_2	D_2H_1	D_2H_2	D_1	D_2
	At the lower air speed, A_1 (100 ft./min)					
R_1	19·3	23·9	34·8	39·3	21·6	37·1
R_2	25·4	27·7	42·9	51·5	26·5	47·2
	At the higher air speed, A_2 (350 ft./min)					
R_1	18·1	18·5	41·5	46·5	18·3	44·0
R_2	24·3	23·2	46·7	53·0	23·7	49·9

TABLE 59

Series V. Increase in sweat loss (grams per kilogram of body weight) per degree Fahrenheit increase in mean radiant temperature at the different environments

D_1 = air temperature, lower level (90°F); D_2 = upper level (110°F)
H_1 = humidity, lower level (16·5 mm Hg); H_2 = upper level (27·0 mm Hg)
A_1 = air speed, lower level (100 ft./min); A_2 = upper level (350 ft./min)
R_1 = added radiant heat, lower level (nil); R_2 = upper level

Environment	$R_2 - R_1$ (°F)	Sweat loss at R_2 − sweat loss at R_1			Increase in sweat loss per °F increase in mean radiant temp.
		Subject A	Subject B	Mean	
A_1 D_1 H_1	21	6·8	5·3	6·1	0·29
H_2	21	3·7	3·9	3·8	0·19
D_2 H_1	22	7·7	8·5	8·1	0·38
H_2	20	13·6	10·8	12·2	0·61
A_2 D_1 H_1	17	5·1	7·4	6·3	0·37
H_2	16	5·4	3·9	4·7	0·24
D_2 H_1	16	4·2	6·4	5·2	0·33
H_2	16	5·1	8·0	6·6	0·41

TABLE 60

Series V. Final rectal temperature. Mean values (°F)

D_1 = air temperature, lower level (90°F); D_2 = upper level (110°F)
H_1 = humidity, lower level (16·5 mm Hg); H_2 = upper level (27·0 mm Hg)
R_1 = added radiant heat, lower level (nil); R_2 = upper level
(at A_1, approx. 21°F)
(at A_2, approx. 16°F)

	D_1 H_1	D_1 H_2	D_2 H_1	D_2 H_2	D_1	D_2
	At the lower air speed, A_1 (100 ft./min)					
R_1	99·3	99·6	99·5	100·5	99·4	100·0
R_2	99·5	99·5	100·2	101·5	99·5	100·8
	At the higher air speed, A_2 (350 ft./min)					
R_1	99·0	99·2	100·6	100·0	99·1	100·3
R_2	99·4	99·3	100·5	100·6	99·3	100·5

TABLE 61

Series V. Final pulse rate. Mean values (beats/30 sec)

D_1 = air temperature, lower level (90°F); D_2 = upper level (110°F)
H_1 = humidity, lower level (16·5 mm Hg); H_2 = upper level (27·0 mm Hg)
R_1 = added radiant heat, lower level (nil); R_2 = upper level
(at A_1, approx. 21°F)
(at A_2, approx. 16°F)

	D_1 H_1	D_1 H_2	D_2 H_1	D_2 H_2	D_1	D_2
	At the lower air speed, A_1 (100 ft./min)					
R_1	42	48	57	71	45	64
R_2	43	43	67	74	43	70
	At the higher air speed, A_2 (350 ft./min)					
R_1	36	43	68	55	39	61
R_2	41	43	70	63	42	66

TABLE 62

Series V. Final skin temperature. Mean values (°F)

D_1 = air temperature, lower level (90°F); D_2 = upper level (110°F)
H_1 = humidity, lower level (16·5 mm Hg); H_2 = upper level (27·0 mm Hg)
R_1 = added radiant heat, lower level (nil); R_2 = upper level
(at A_1, approx. 21°F)
(at A_2, approx. 16°F)

	D_1 H_1	D_1 H_2	D_2 H_1	D_2 H_2	D_1	D_2
	At the lower air speed, A_1 (100 ft./min)					
R_1	92·3	93·8	95·2	97·9	93·0	96·5
R_2	92·1	93·9	97·2	97·1	93·0	97·1
	At the higher air speed, A_2 (350 ft./min)					
R_1	89·6	90·6	96·6	95·1	90·1	95·8
R_2	91·0	92·5	96·2	96·0	91·7	96·1

TABLE 63

Series VI. Sweat loss per kilogram body weight. Analysis of variance

D = air temperature; H = humidity; A = air speed;
R = radiant heat; N = clothing; S = subject

Source of variation	D.F.	Sums of squares	Mean square	Error term	F
D	1	30,125·13	30,125·13		
H	1	1,480·74	1,480·74		
A	2	53·74	26·87	E	13·20***
R	3	803·98	267·99	E	131·63***
N	1	441·04	441·04	S N	3·71
D H	1	325·52	325·52	S	3·19
D A	2	9·86	4·93	E	2·42
D R	3	45·39	15·13	E	7·43***
D N	1	0·06	0·06	S	—
H A	2	116·76	58·38	E	28·76***
H R	3	2·81	0·94	E	—
H N	1	55·47	55·47	S	0·54
A R	6	18·19	3·03	E	—
A N	2	94·72	47·36	E	23·26***
R N	3	5·31	1·77	E	—
D H A	2	32·26	16·13	S A	—
D H R	3	7·69	2·56	S R	—
D H N	1	23·52	23·52	S N	—
D A R	6	15·31	2·55	E	—
D A N	2	32·15	16·08	S A	1·88
D R N	3	4·82	1·61	S R	1·28
H A R	6	12·07	2·01	E	—
H A N	2	2·09	1·05	S A	—
H R N	3	0·41	0·14	S R	—
A R N	6	8·56	1·43	E	—
D H A R	6	17·16	2·86	E	—
D H A N	2	1·28	0·64	E	—
D H R N	3	4·28	1·43	E	—
D A R N	6	7·73	1·29	E	—
H A R N	6	7·76	1·29	E	—
D H A R N	6	0·93	0·16	E	—
S	4	408·49	102·12		
S A	8	68·45	8·56		
S N	4	475·40	118·85		
S R	12	15·12	1·26	2·036 80 D.F.	
S A R	24	42·68	1·78		
S A N	8	16·45	2·06		
S R N	12	12·42	1·04		
S A R N	24	76·24	3·18		
Total	191	34,871·99			

*** Significant at the 0·1% level

TABLE 64

Series VI. Sweat loss per kilogram body weight. Mean values (grams)

D = dry-bulb temperature; H = humidity; A = air speed; R = radiant heat; N = clothing

Air temperature × radiant heat

	R_1 (increment 0°F)	R_2 (increment 5·4°F)	R_3 (increment 10·8°F)	R_4 (increment 16·2°F)	Mean
D_1 (90°F)	21·1	22·2	24·2	25·2	23·2
D_2 (110°F)	44·6	47·3	50·0	51·0	48·2
Mean	32·9	34·8	37·1	38·1	

Humidity × air speed

	A_1 (150 ft./min)	A_2 (200 ft./min)	A_3 (350 ft./min)	Mean
H_1 (16·5 mm Hg)	32·7	32·6	33·5	32·9
H_2 (27·0 mm Hg)	40·2	38·1	37·2	38·5
Mean	36·5	35·4	35·3	

Air speed × clothing

	A_1	A_2	A_3	Mean
N_1 (shorts)	34·3	33·6	34·8	34·2
N_2 (overalls)	38·7	37·1	35·9	37·2

Air temperature × humidity

	H_1	H_2
D_1	21·7	24·7
D_2	44·2	52·3

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = ·05$	$P = ·01$
R	48	0·58	0·77
D × R	24	0·82	1·09
A	64	0·50	0·67
H × A	32	0·71	0·94
A × N	32	0·71	0·94

TABLE 65

Series VI. Component mean squares due to the effect of increasing the mean radiant temperature

Source of variation		Degrees of freedom	Sum of squares
R	linear	1	784·09***
	quadratic	1	10·92*
	cubic	1	8·97*

* Significant at 5% level
*** Significant at 0·1% level

TABLE 66

Series VI. Final rectal temperature. Mean values (°F)

D = dry-bulb temperature; H = humidity; A = air speed; R = radiant heat; N = clothing

Air temperature × humidity

	H₁ (16·5 mm Hg)	H₂ (27·0 mm Hg)	Mean
D_1 (90° F)	99·29	99·23	99·26
D_2 (110° F)	99·73	100·43	100·08
Mean	99·51	99·83	

Humidity × air speed

	A_1 (150 ft./min)	A_2 (200 ft./min)	A_3 (350 ft./min)
H_1	99·53	99·50	99·51
H_2	99·97	99·82	99·71
Mean	99·75	99·66	99·61

Humidity × clothing

	H_1	H_2	Mean
N_1 (shorts)	99·55	99·47	99·51
N_2 (overalls)	99·48	100·19	99·84

Temperature × air speed × radiant heat

		R_1 (increment 0° F)	R_2 (increment 5·4° F)	R_3 (increment 10·8° F)	R_4 (increment 16·2° F)
D_1	A_1	99·24	99·23	99·53	99·23
	A_2	99·20	99·21	99·21	99·58
	A_3	99·08	99·14	99·19	99·34
D_2	A_1	99·86	100·05	100·29	100·55
	A_2	99·86	99·86	100·21	100·14
	A_3	99·88	99·90	100·20	100·18
Mean		99·52	99·56	99·77	99·83

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot05$	$P = \cdot01$
D × H	48	0·47	0·78
A	64	0·10	0·13
N	96	0·33	0·54
H × N	48	0·47	0·78
R	48	0·11	0·15
D × A × R	8	0·27	0·36

TABLE 67

Series VI. Final standing pulse rate. Mean values (beats/30 sec)

D = dry-bulb temperature; H = humidity; A = air speed; R = radiant heat; N = clothing

Air temperature × air speed

	A_1 (150 ft./min)	A_2 (200 ft./min)	A_3 (350 ft./min)	Mean
D_1 (90°F)	44	42	42	43
D_2 (110°F)	60	61	59	60
Mean	52	51	50	

Air temperature × radiant heat

	R_1 (increment 0°F)	R_2 (increment 5·4°F)	R_3 (increment 10·8°F)	R_4 (increment 16·2°F)
D_1	43	41	43	43
D_2	56	60	61	64
Mean	49	51	52	54

Humidity × air speed

	A_1	A_2	A_3	Mean
H_1 (16·5 mm Hg)	47	48	48	48
H_2 (27·0 mm Hg)	58	55	52	55

Humidity × radiant heat

	R_1	R_2	R_3	R_4
H_1	46	47	48	49
H_2	52	54	56	59

Humidity × clothing

	H_1	H_2	Mean
N_1 (shorts)	47	51	49
N_2 (overalls)	48	59	53

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = ·05$	$P = ·01$
A	64	1·14	1·52
D × A	32	1·62	2·15
R	48	1·32	1·75
D × R	24	1·78	2·48
H × A	32	1·62	2·15
H × R	24	1·78	2·48
N	96	4·11	6·80

TABLE 68

Series VI. Final skin temperature. Mean values (°F)

D = dry-bulb temperature; H = humidity; A = air speed; R = radiant heat; N = clothing

Radiant heat

R_1 (increment 0°F)	R_2 (increment 5·4°F)	R_3 (increment 10·8°F)	R_4 (increment 16·2°F)
93·80	93·95	94·11	94·48

Humidity × air speed

	A_1 (150 ft./min)	A_2 (200 ft./min)	A_3 (350 ft./min)	Mean
H_1 (16·5 mm Hg)	93·58	93·33	93·19	93·37
H_2 (27·0 mm Hg)	95·21	94·88	94·33	94·81
Mean	94·39	94·10	93·76	

Air temperature × humidity

	H_1	H_2	Mean
D_1 (90°F)	91·61	92·43	92·02
D_2 (110°F)	95·13	97·19	96·16

Air temperature × clothing; humidity × clothing

	D_1	D_2	H_1	H_2	Mean
N_1 (shorts)	91·28	95·90	93·18	93·99	93·59
N_2 (overalls)	92·75	96·42	93·55	95·62	94·59

Significant differences for comparing means

Source of variation	No. of values in each mean	P = ·05	P = ·01
R	48	0·25	0·34
A	64	0·19	0·25
H × A	32	0·26	0·35

TABLE 69

Series VI. Comparison of results of analyses of variance, showing significant effects involving R *(radiant heat)*

D = air temperature; H = humidity; A = air speed; N = clothing

Source of variation	Variance ratio					
	Sweat loss/kg body weight	Final rectal temp.	Final pulse rate	Final skin temp.	Skin temp. after Work III	Skin temp. in middle long rest
R	131·63***	15·07***	17·55***	14·75***	11·81***	12·13***
D × R	7·43***	—	12·45***	—	—	—
H × R	—	—	4·15**	—	—	—
A × R	—	—	—	—	—	—
N × R	—	—	—	—	—	—
D × H × R	—	—	7·67*	—	—	—
D × A × R	—	2·80*	—	—	—	—

* Significant at the 5% level
** Significant at the 1% level
*** Significant at the 0·1% level

TABLE 70

Series VII. Sweat loss per kilogram body weight. Analysis of variance

S = subject; A = air speed; R = radiant heat; N = clothing

Source of variation	D.F.	Sum of squares	Mean square	F
S	2	138·14	69·07	33·05***
A	1	4·44	4·44	—
R L†	1	651·42	651·42	311·68***
R Q	1	5·74	5·74	—
R C	1	4·21	4·21	—
N	1	446·52	446·52	213·65***
S A	2	1·72	0·86	—
S R	6	4·04	0·67	—
S N	2	3·35	1·68	—
A R	3	1·33	0·44	—
A N	1	42·56	42·56	20·36***
R N	3	2·24	0·75	—
S A R	6	18·86	2·09	—
S A N	2	6·06		
S R N	6	10·06		
A R N	3	1·98		
S A R N	6	11·21		
Total	47	1,353·88	—	—

† L, Q & C = the linear, quadratic and cubic components
*** Significant at the 0·1% level

TABLE 71

Series VII. Sweat loss per kilogram body weight. Mean values (grams)

A = air speed; R = radiant heat; N = clothing; S = subjects

Radiant heat

R_1 (increment 0°F)	R_3 (increment 10·8°F)	R_5 (increment 21·6°F)	R_7 (increment 32·4°F)
35·8	39·0	41·5	46·0

Air speed × clothing

	A_2 (200 ft./min)	A_3 (350 ft./min)	Mean
N_1 (shorts)	36·9	38·1	37·5
N_2 (overalls)	44·9	42·4	43·6

Subjects

S_1	S_2	S_3
42·9	39·8	39·0

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot05$	$P = \cdot01$
R	12	1·22	1·66
N	24	0·86	1·17
A × N	12	1·22	1·66
S	16	1·06	1·44

TABLE 72

Series VII. Final rectal temperature. Mean values (°F)

A = air speed; R = radiant heat; N = clothing; S = subjects

Subjects × radiant heat

	R_1 (increment 0°F)	R_3 (increment 10·8°F)	R_5 (increment 21·6°F)	R_7 (increment 32·4°F)	Mean
S_1	99·95	99·98	100·48	100·55	100·24
S_2	99·33	99·58	99·58	99·95	99·61
S_3	99·80	99·80	100·18	100·45	100·06
Mean	99·69	99·78	100·08	100·32	

Air speed × radiant heat

	R_1	R_3	R_5	R_7	Mean
A_2 (200 ft./min)	99·73	99·82	100·12	100·48	100·04
A_3 (350 ft./min)	99·65	99·75	100·03	100·15	99·90

Air speed × clothing

	A_2	A_3	Mean
N_1 (shorts)	99·78	99·78	99·78
N_2 (overalls)	100·29	100·01	100·15

Radiant heat × clothing

	R_1	R_3	R_5	R_7
N_1	99·63	99·50	99·83	100·17
N_2	99·75	100·07	100·32	100·47

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot05$	$P = \cdot01$
S	16	0·090	0·123
R	12	0·104	0·142
S × R	4	0·131	0·245
A	24	0·074	0·100
A × R	6	0·147	0·200
N	24	0·074	0·100
A × N	12	0·104	0·142
R × N	6	0·147	0·200

TABLE 73

Series VII. Final standing pulse rate. Mean values (beats/30 sec)

A = air speed; R = radiant heat; N = clothing; S = subjects

Radiant heat × clothing

	R_1 (increment 0°F)	R_3 (increment 10·8°F)	R_5 (increment 21·6°F)	R_7 (increment 32·4°F)	Mean
N_1 (shorts)	50	53	54	57	53
N_2 (overalls)	56	63	65	75	65
Mean	53	58	59	66	

Air speed × clothing

	N_1	N_2
A_2 (200 ft./min)	53	68
A_3 (350 ft./min)	53	62

Subjects × clothing

	N_1	N_2	Mean
S_1	52	61	56
S_2	52	67	59
S_3	56	67	61

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot05$	$P = \cdot01$
R	12	4·02	5·46
N	24	2·84	3·86
R × N	6	5·69	7·72
A × N	12	4·02	5·46
S	16	3·48	4·73

TABLE 74

Series VII. Final skin temperature. Mean values (°F)

A = air speed; R = radiant heat; N = clothing: S = subjects

Radiant heat

R_1 (increment 0°F)	R_3 (increment 10·8°F)	R_5 (increment 21·6°F)	R_1 (increment 32·4°F)
93·78	94·41	95·08	95·62

Air Speed

A_2 (200 ft./min)	A_3 (350 ft./min)
95·12	94·33

Subjects × clothing

	S_1	S_2	S_3	Mean
N_1 (shorts)	93·09	94·63	94·35	94·02
N_2 (overalls)	95·09	95·79	95·39	95·42
Mean	94·09	95·21	94·87	

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot05$	$P = \cdot01$
R	12	0·24	0·33
A	24	0·17	0·23
S	16	0·21	0·29
N	24	0·17	0·23
S × N	8	0·30	0·41

TABLE 75

Series VII. Comparison of the analyses of variance of the values for the several physiological effects

A = air speed; R = radiant heat; N = clothing: S = subjects

Source of variation	Variance ratio					
	Sweat loss/kg body weight	Final rectal temp.	Final pulse rate	Final skin temp.	Skin temp. after Work III	Skin temp. in middle long rest
S	33·05***	112·67***	4·94*	62·74***	21·60***	48·72***
A	—	16·00***	—	89·52***	73·13***	23·64***
R†	311·68***	188·06***	41·68***	271·67***	141·80***	80·47***
N	213·65***	107·33**	70·07***	280·00***	312·27***	11·71**
S × A	—	—	—	—	—	—
S × R	—	3·33*	—	—	—	—
S × N	—	—	—	13·10***	7·77**	12·33***
A × R	—	3·33*	—	—	—	—
A × N	20·36***	16·00***	4·77*	—	5·08*	13·95**
R × N	—	8·00**	3·18*	—	—	4·98**

† Linear component of sums of squares only
* Significant at the 5% level
** Significant at the 1% level
*** Significant at the 0·1% level

TABLE 76

Series VI. The calculated contribution of metabolism, radiation and convection to the total heat load, together with the evaporative heat equivalent of the observed sweat loss, at two levels of radiant heat and two air temperatures. Mean values (B.Th.U.) for H_1 *and* H_2 *(16·5 and 27·0 mm Hg) for subjects wearing shorts at air speed 200 ft./min*

Mean radiant temp. (°F)	Air temp. (°F)	Metabolism	Radiation	Convection	M + R + C	Heat equivalent of sweat loss
90 (R_1)	90	748	−47	−77	624	724
106·2 (R_4)	90	748	236	−107	877	856
110 (R_1)	110	748	275	428	1451	1502
126·2 (R_4)	110	748	629	419	1796	1718

TABLE 77

Series VII. The calculated contribution of metabolism, radiation and convection to the total heat load, together with the evaporative heat equivalent of the observed sweat loss, at four levels of radiant heat and two air speeds. Values (B.Th.U.) for subjects wearing shorts at air temperature 100°F, humidity 27·0 mm Hg

Mean radiant temp. (°F)	Air speed (ft./min)	Metabolism	Radiation	Convection	M + R + C	Heat equivalent of sweat loss
100 (R_1)	200	748	120	193	1061	1207
	350	748	124	263	1135	1287
110·8 (R_3)	200	748	316	172	1236	1374
	350	748	322	240	1310	1406
121·6 (R_5)	200	748	533	163	1444	1435
	350	748	537	224	1509	1507
132·4 (R-)	200	748	755	143	1646	1637
	350	748	772	220	1740	1637

TABLE 78

Data of Humphreys et al. (1946) showing the change in rectal temperature produced by increasing the mean radiant temperature by 40°F at successive levels of effective temperature

Effective temperature (°F)	Rectal temperature (°F)		
	No added radiant heat	Mean radiant temperature + 40°F	Increase
90	99·65	100·24	0·59
91	99·80	100·47	0·67
92	99·98	100·90	0·92
93	100·30	101·60	1·30

TABLE 79

Series VI. Deviations from regression of sweat loss on corrected effective temperature. Mean values (g/kg body weight) for the interaction of air temperature (D) *and added radiant heat* (R)

	R_1 (increment 0°F)	R_2 (increment 5·4°F)	R_3 (increment 10·8°F)	R_4 (increment 16·2°F)	Mean
D_1 (90°F)	0·1	−0·3	0·3	−0·3	−0·1
D_2 (110°F)	−1·4	−0·3	0·9	0·2	−0·1
Mean	−0·6	−0·3	0·6	−0·04	−0·1

Tables to Chapter 7

TABLE 80

Series VIIIa. Mean values for resting energy expenditure and sweat loss

Subject	Energy expenditure (kcal/hr)			Sweat loss (g/hr)		
	Total	/m² body surface	/kg body weight	Total	/m² body surface	/kg body weight
P	93·4	50·5	1·34	115	62	1·65
M	85·1*	45·4	1·20	104**	55	1·46
B	95·1	55·0	1·40	129	75	1·90
W	91·8	55·5	1·49	138	83	2·24

* The value for subject M is significantly less than for subjects W, P and B ($P < ·01$)
** The value for subject M is significantly less than for subjects B and W ($P < ·01$) and subject P ($P < ·05$)

TABLE 81

Series VIIIa. Mean values for net walking energy expenditure and sweat loss

Subject	Energy expenditure (kcal/hr)			Sweat loss (g/hr)		
	Total	/m² body surface	/kg body weight	Total	/m² body surface	/kg body weight
P	181·1	97·9	2·60	321	174	4·60
M	151·4*	80·7	2·13	251**	134	3·53
B	177·1	102·5	2·61	367	212	5·41
W	162·2	98·0	2·63	338	204	5·48

* The value for subject M is significantly less than for subjects W, P and B (*P* = ·01)
** The value for subject M is significantly less than for subjects B and W (*P* = ·01) and for P (*P* = ·05)

TABLE 82

Series VIIIa. Net walking energy expenditure. Mean values for significant effects

(a) kcal/hr

Subject	P	M	B	W
	181·06	151·42	177·14	162·17

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	104·21	124·77	143·48	167·63	202·20	255·16
B & W	94·61	119·80	144·50	170·33	207·94	280·75
Subject × speed						
B	101·65	109·99	158·53	169·13	222·57	301·01
W	87·58	129·62	130·48	171·53	193·32	260·50

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	12	9·287	12·623
Speed	4	16·085	21·863
Subject × speed	2	22·748	30·919

(b) kcal/hr/kg

Subject	P	M	B	W
	2·600	2·130	2·613	2·632

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	1·486	1·778	2·040	2·392	2·874	3·619
B & W	1·462	1·861	2·223	2·646	3·204	4·340
Subject × speed						
B	1·509	1·618	2·340	2·494	3·271	4·449
W	1·416	2·104	2·107	2·798	3·137	4·231

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	12	0·1406	0·1911
Speed	4	0·2436	0·3311
Subject × speed	2	0·3445	0·4682

TABLE 83

Series VIIIa. Net walking sweat loss. Mean values for significant effects

(a) g/hr

Subject	P	M	B	W
	321	251	367	338

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	137	224	235	294	352	472
B & W	180	225	301	374	442	593

Time	1st half of series	2nd half of series
P & M	275	297
B & W	366	339

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot 05$	$P = \cdot 01$
Subject	12	20·2	27·5
Speed	4	35·0	47·6
Time	12	20·2	27·5

(b) g/kg/hr

Subject	P	M	B	W
	4·60	3·53	5·41	5·48

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	1·95	3·19	3·35	4·20	5·01	6·70
B & W	2·77	3·47	4·63	5·81	6·80	9·20

Time	1st half of series	2nd half of series
P & M	3·91	4·22
B & W	5·65	5·24

Subject × speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
B	3·01	3·36	4·99	5·49	6·93	8·70
W	2·54	3·58	4·27	6·12	6·68	9·71

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot 05$	$P = \cdot 01$
Subject	12	0·295	0·401
Speed	4	0·511	0·695
Time	12	0·295	0·401
Subject × speed	2	0·723	0·983

TABLE 84

Series VIIIa. Net walking sweat loss per unit of energy expenditure. Mean values (g/kcal) for significant effects

Subject	P	M	B	W
	1·74	1·62	2·09	2·02

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	1·31	1·80	1·63	1·76	1·75	1·85

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	12	0·192	0·261
Speed	4	0·333	0·452

TABLE 85

Series VIIIa. Pulse rate. Mean values (beats/30 sec) of recordings at three stages (105, 120 and 135 min) during work. Significant effects only

Subject	P	M	B	W
	47	42	48	43

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	41	44	42	46	46	51
B & W	39	43	43	44	49	55
Subject × speed						
B	41	46	43	47	54	56
W	38	39	44	41	45	53
Stage × speed (P & M only)						
105 min	41	43	42	48	45	51
120 min	41	44	42	45	45	51
135 min	40	44	42	44	46	50

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	36	1·45	2·03
Speed	12	2·50	3·51
Subject × speed	6	3·54	4·96
Stage × speed	4	1·88	2·49

TABLE 86

Series VIIIa. Skin temperature. Mean values (°F) of recordings at two stages during work and two stages after work. Significant effects only

Subject	P	M	B	W
	92·09	92·32	91·56	91·87

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	92·69	92·71	92·29	91·88	91·87	91·81
B & W	91·86	91·88	91·68	91·27	91·41	92·17

Stage

	105 min	120 min	155 min	165 min
P & M	91·39	91·16	92·77	93·50

Subject × time

	1st half of series	2nd half of series
P	92·33	91·86
M	92·21	92·42

Subject × stage

	105 min	120 min	155 min	165 min
B	90·45	90·48	92·09	93·22
W	91·35	90·93	92·06	93·13

Speed × stage (subjects P & M only)

	105 min	120 min	155 min	165 min
2·0 m.p.h.	92·25	91·79	93·15	93·59
2·4 m.p.h.	91·90	91·73	93·28	93·92
2·8 m.p.h.	91·59	90·85	92·94	93·79
3·2 m.p.h.	91·19	90·76	92·27	93·28
3·6 m.p.h.	90·82	90·77	92·65	93·23
4·0 m.p.h.	90·60	91·06	92·36	93·22

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	48	0·320	0·437
Speed	16	0·555	0·756
Stage	24	0·213	0·284
Subject × time	24	0·453	0·618
Subject × stage	12	0·302	0·401
Speed × stage	4	0·523	0·695

TABLE 87

Series VIIIa. Rectal temperature. Mean values (°F) of thermocouple measurements recorded at five stages during work and two stages after work. Significant effects only

Subject	P	M	B	W
	99·22	99·20	99·50	99·24

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	99·06	99·05	99·35	99·48	99·11	99·22
B & W	99·31	99·35	99·05	99·40	99·49	99·63

Time	1st half of series	2nd half of series
P & M	99·14	99·29
B & W	99·26	99·49

Stage	100 min	105 min	120 min	135 min	145 min	155 min	165 min
P & M	99·16	99·23	99·29	99·29	99·28	99·17	99·05
B & W	99·42	99·47	99·47	99·41	99·38	99·32	99·13

Subject × stage							
P	99·23	99·29	99·34	99·31	99·28	99·11	99·00
M	99·10	99·17	99·24	99·27	99·28	99·23	99·11

Subject × time	1st half of series	2nd half of series
P	99·05	99·40
M	99·23	99·17

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	84	0·117	0·166
Speed	28	0·203	0·288
Time	84	0·117	0·166
Stage	24	0·067	0·089
Subject × stage	12	0·095	0·126
Subject × time	42	0·165	0·235

TABLE 88

Series VIIIa. Net walking energy expenditure per unit of body weight per mile walked. Mean values (kcal/kg/mile) for significant effects

Subject	P	M	B	W
	0·861	0·693	0·844	0·857

Speed	2·0 m.p.h.	2·4 m.p.h.	2·8 m.p.h.	3·2 m.p.h.	3·6 m.p.h.	4·0 m.p.h.
P & M	0·743	0·741	0·729	0·748	0·798	0·905
B & W	0·732	0·775	0·794	0·827	0·890	1·085

Subject × speed						
B	0·755	0·624	0·836	0·780	0·909	1·113
W	0·708	0·877	0·753	0·875	0·871	1·058

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Subject	12	0·0540	0·0734
Speed	4	0·0936	0·1272
Subject × speed	2	0·1323	0·1799

TABLE 89

Series VIIIa. Mean values (kg) by which the calculated sweat loss for four hours exceeded the P4SR values

Speed (m.p.h.)	Subject P	Subject M	Subject B	Subject W	Mean
2·0	·059	·110	·265	·234	·167
2·4	·173	·295	·331	·123	·231
2·8	·169	·111	·368	·299	·236
3·2	·250	·246	·423	·390	·327
3·6	·240	·266	·299	·308	·278
4·0	·297	·234	·216	·445	·298
Mean	·198	·210	·317	·300	

TABLE 90

Series VIIIa. Distribution of the heat exchange during the period 90–170 min. Mean values for the three higher and three lower walking speeds for each pair of subjects

M = heat production; S = heat storage; E_1 = heat loss by evaporation of sweat;
E_2 = heat loss by evaporation from respiratory tract; C = heat loss by convection;
R = heat loss by radiation; W = heat loss by drinking cold water

Subject pair	Walking speed	Heat exchange (B.Th.U.)						
		M	S	E_1	E_2	C	R	W
P & M	Low	949	8	715	35	113	52	34
P & M	High	1282	24	1104	44	70	32	34
B & W	Low	961	38	841	35	59	31	34
B & W	High	1356	30	1291	46	47	22	34

TABLE 91

Series VIIIa. Comparison of the heat lost by evaporation of sweat during the period 90–170 min with the calculated maximum possible heat loss by this means during the same period

Subject pair	Walking speed	Heat loss (B.Th.U.)		
		Observed	Calculated maximum	Observed as % of maximum
P & M	Low	715	1774	40
P & M	High	1104	1654	67
B & W	Low	839	1494	56
B & W	High	1291	1463	88

TABLE 92

Series VIIIa. Comparison of the observed energy expenditure of the four subjects with the values predicted by Mahadeva et al. (1953)

Subjects	Energy expenditure (kcal/hr)	
	Observed	Predicted
P	255·8	263·3
M	224·3	267·6
B	257·9	252·5
W	238·0	241·0

TABLE 93

Series VIIIb. Net energy expenditure and sweat loss. Mean values for significant effects

Energy expenditure (kcal/hr)

Subject

P	M	B	W
112·9	101·2	92·7	84·6

Routine (P & M only)			*Work period (B & W only)*	
I	II	III	First	Second
116·3	95·9	108·9	91·4	85·9

Significant differences for comparing means

Source of variation	*P* = ·05	*P* = ·01
Subject: P & M	4·39	5·99
B & W	2·45	3·34
Routine	3·41	5·65
Work period	2·45	3·34

Sweat loss (g/hr)

Subject

P	M	B	W
216·9	180·2	221·8	177·3

Routine (P & M only)

I	II	III
211·5	165·0	219·2

Significant differences for comparing means

Source of variation	*P* = ·05	*P* = ·01
Subject: P & M	8·17	11·88
B & W	16·88	23·02
Routine	42·52	70·52

TABLE 94

Series VIIIb. Sweat loss per unit of energy expenditure. Mean values (g/kcal)

Subject

P	M	B	W
1·921	1·776	2·401	2·096

Work period (P & M only)

First	Second
1·812	1·884

Subject × work period

	P	M
First work period	1·843	1·781
Second work period	1·999	1·770

Significant differences for comparing means

Source of variation	*P* = ·05	*P* = ·01
Subject: P & M	0·067	0·091
B & W	0·183	0·249
Work period	0·067	0·091
Subject × work period	0·095	0·129

TABLE 95

Series VIIIb. Rectal temperature. Comparison of mean values (°F) recorded before and after work in the three routines

Subject pair		Routine I	Routine II	Routine III
P & M	Before work	98·75	98·80	98·93
	After work	98·75	98·78	98·79
B & W	Before work	98·93	98·91	98·86
	After work	98·81	98·90	98·70

TABLE 96

Series VIIIb. Skin temperature. Comparison of mean values (°F) in the three routines

Subject pair	Routine I	Routine II	Routine III
P & M	91·90	92·10	92·16
B & W	91·75	90·98	91·68

TABLE 97

Series VIIIc. The mean values for total energy expenditure on step-climbing and the values expressed as functions of body weight and surface area, together with the mean values for resting energy expenditure per unit surface area

Subject	Step-climbing			Resting
	kcal/hr	kcal/kg/hr	kcal/m²/hr	kcal/m²/hr
P	313·6	4·448	169·3	52·1
M	297·8	4·236	159·4	47·2
B	286·6	4·263	166·4	57·0
W	283·1	4·686	172·5	62·8
Mean	295·3	4·408	166·9	54·8
Significant differences 5% level:	14·35	0·2076	7·96	4·49
Significant differences 1% level:	20·12	0·2911	11·16	6·34

TABLE 98

Comparison of the estimates of energy expenditure per unit surface area for the component activities of the 'Queen Square Routine'

Series	Energy expenditure (kcal/m²/hr)				
	Resting	S.D.	Stepping	S.D.	Mean for 'Queen Sq. Routine'
Dunham *et al.* (1946)	54	—	180	—	111·75
Adam *et al.* (1952)	48	—	162	—	100·25
Adam and Cague (1952)	46·82	3·47	164·01	7·00	100·53
Series VIIIc	54·80	2·88	166·90	5·16	106·20

TABLE 99

Comparison of the physical characteristics of the subjects in Series VIIIc with those of Dunham et al. (1946) *and Adam and Cague* (1952)

Series	Height (cm)	Weight (kg)	Surface area (m²)
Dunham *et al.* (1946)	171·0	66·0	1·77
Adam and Cague (1952)	172·1	64·3	1·76
Series VIIIc	169·2	67·5	1·78

Tables to Chapter 8

TABLE 100

Series IX. Sweat loss during the first two hours, and rectal temperature and pulse rate after the fourth work period during the 12 days acclimatization. Mean values

Day	Sweat loss (g/kg body weight)	Rectal temperature (F)	Standing pulse rate (beats/30 sec)
8	24·10	100·21	57
9	25·15	100·22	58
10	26·39	100·36	56
11	26·96	100·31	60
12	28·65	100·21	56
13	29·41	100·21	58
14	28·63	100·03	53
15	30·84	100·14	53
16	30·70	100·05	53
17	31·59	100·03	53
18	32·09	99·86	55
19	32·69	99·86	54

TABLE 101

Series IX. The effect of three levels of water intake on the mean sweat loss during the four-hour experiments of the last 6 days of acclimatization

Hour	Sweat loss (g/kg body weight)			
	Treatment A (550 ml.)	Treatment B (700 ml.)	Treatment C (850 ml.)	Mean
1	13·243	13·177	13·500	13·307
2	17·439	17·679	18·229	17·782
3	14·995	15·666	16·438	15·700
4	12·248	12·898	13·799	12·982
Mean	14·481	14·855	15·492	

Significant differences for comparing means

Source of variation	No. of values in each mean	$P = \cdot 05$	$P = \cdot 01$
Treatment	96	0·415	0·552
Hour	72	0·238	0·314
Treatment × hour	24	0·412	0·544

TABLE 102

Series IX. The effect of three levels of water intake on the mean rectal temperature at the end of the third work period throughout the acclimatization period

Treatment (water intake)	A (550 ml.)	B (700 ml.)	C (850 ml.)
Rectal temperature (F)	100·19	100·01	99·98

Significant differences for comparing means (48 values)

$P = \cdot 05$, 0·073 $P = \cdot 01$, 0·097

TABLE 103

Series IX. The effect of three levels of water intake on the mean rectal temperature after the first, third, fifth and seventh work periods of the four-hour experiments of the last 6 days of acclimatization

Hour	Rectal temperature (°F)			
	Treatment A (550 ml.)	Treatment B (700 ml.)	Treatment C (850 ml.)	Mean
End of Work I	98·95	98·97	98·94	98·95
End of Work III	100·06	99·88	99·83	99·93
End of Work V	100·44	100·26	100·17	100·29
End of Work VII	100·68	100·44	100·31	100·48
Mean	100·03	99·89	99·81	

Significant differences for comparing means

Source of variation	No. of values in each mean	*P* = ·05	*P* = ·01
Hour	72	0·45	0·59
Treatment	96	0·079	0·104
Hour × treatment	24	0·077	0·102

TABLE 104

Series IX. The effect of three levels of water intake on the mean rectal temperature after the second, fourth, sixth and eighth work periods of the four-hour experiments of the last 6 days of acclimatization

Hour	Rectal temperature (°F)			
	Treatment A (550 ml.)	Treatment B (700 ml.)	Treatment C (850 ml.)	Mean
End of Work II	99·69	99·54	99·52	99·58
End of Work IV	100·12	100·02	99·85	99·99
End of Work VI	100·40	100·22	100·10	100·24
End of Work VIII	100·55	100·35	100·17	100·36
Mean	100·19	100·03	99·91	

TABLE 105

Series IX. The effect of three levels of water intake on the mean pulse rate after the first, third, fifth and seventh work periods during the four-hour experiments of the last 6 days of acclimatization

Treatment (water intake)	A (550 ml.)	B (700 ml.)	C (850 ml.)
Pulse rate (beats /30 sec)	60·7	59·2	58·1

Significant differences for comparing means (96 values)

P = ·05, 1·79 *P* = ·01, 2·35

TABLE 106

Series IX. The effect of three levels of water intake on the mean pulse rate after the second, fourth, sixth and eighth work periods of the four-hour experiments of the last 6 days of acclimatization

Time	Pulse rate (beats/30 sec)			
	Treatment A (550 ml.)	Treatment B (700 ml.)	Treatment C (850 ml.)	Mean
End of Work II	51·9	50·1	49·4	50·5
End of Work IV	54·8	53·4	52·3	53·5
End of Work VI	59·8	56·6	55·8	57·4
End of Work VIII	61·6	57·7	57·5	58·9
Mean	57·0	54·4	53·8	

TABLE 107

Series IX. Uniformity trials. Sweat losses, rectal temperatures and sitting and standing pulse rates at the end of the two-hour period. Mean values

Day	Sweat loss (g/kg)	Rectal temperature (°F)	Sitting pulse rate (beats/30 sec)	Standing pulse rate (beats/30 sec)
7	21·60	100·3	50	60
20	33·28	100·0	47	55
23	35·10	100·0	46	54
25	32·60	99·9	46	54
28	33·46	100·3	49	59
32	33·14	100·3	46	54
35	32·53	100·0	44	50
39	36·50	100·3	47	57
42	34·31	100·1	46	55
46	34·27	100·1	47	55
57	34·82	100·1	48	58

TABLE 108

Series IX. The effect of severe climates. Mean values for rectal temperatures and standing pulse rates after the second work period for eleven men, and four-hour sweat losses for the survivors only, in eleven climates (average air speed 150 *ft./min)*

Expt No.	Climate				Rectal temp. after 100 min (°F)	Pulse rate after 100 min (beats/30 sec)	No. of survivors	Sweat loss for survivors (litres/4 hr)
	Dry-bulb temp. (°F)	Wet-bulb temp. (°F)	'Normal' effective temp. (°F)	Vapour pressure (mm Hg)				
1	91·4	91·0	89·5	37·2	100·7 ± 0·47	67 ± 7·9	11	4·24 ± 0·652
2	92·4	92·0	90·8	38·3	100·9 ± 0·58	71 ± 8·6	9	4·67 ± 0·691
3	96·0	92·0	91·8	37·3	101·9 ± 0·35	79 ± 9·4	9	4·53 ± 0·691
4	100·0	92·0	92·8	36·1	101·4 ± 0·41	76 ± 4·4	11	4·93 ± 0·603
5	100·0	94·0	94·5	39·2	102·4 ± 0·35	81 ± 5·7	—*	—
6	105·0	92·0	93·9	34·8	101·7 ± 0·38	74 ± 8·2	10	5·06 ± 0·663
7	110·0	91·0	94·1	31·8	101·9 ± 0·45	80 ± 3·2	9	4·97 ± 0·556
8	115·0	90·0	94·2	29·2	101·5 ± 0·33	77 ± 4·2	10**	4·85 ± 0·474
9	120·0	89·0	94·4	26·3	101·3 ± 0·40	74 ± 5·3	11	5·12 ± 0·596
10	120·0	91·0	95·5	29·2	102·2 ± 0·50	79 ± 8·2	—*	—
11	130·0	89·0	95·6	23·5	101·7 ± 0·44	79 ± 5·1	8	5·73 ± 0·523

* Five casualties; experiment abandoned after third work period
** One subject removed for medical reasons

TABLE 109

Series IX. The effect on rectal temperature and pulse rate of reducing the air speed. Mean values for ten men except where bracketed numbers indicate otherwise

Time	Air speed 150 ft./min (Dry-bulb 120 °F, Wet-bulb 89 °F)		Air speed 20 ft./min (Dry-bulb 120 °F, Wet-bulb 88·3 °F)	
	Rectal temperature (°F)	Pulse rate (beats/30 sec)	Rectal temperature (°F)	Pulse rate (beats/30 sec)
Before Experiment	98·4	43	98·6	43
After Work I	100·3	67	100·2	65
After Rest I	100·4	55	100·4	63
After Work II	101·2	74	101·6	80
After Rest II	100·6	62	101·2(7)	71(7)
After Work III	101·4	77	101·7(6)	79(6)
After Rest III	99·9	56	—	—
End of Experiment	100·7	72		—

TABLE 110

Series IX. The effect of radiant heat and clothing variations on rectal temperatures, pulse rates and four-hour sweat losses. Mean values for five men. Experiments conducted at dry-bulb 115°F, wet-bulb 90°F, air speed 150 ft./min

Expt.	Mean radiant temp. (°F)	Clothing	Rectal temp. at end of Work III (°F)	Pulse rate at end of Work III (beats/30 sec)	Sweat loss in 4 hr (g/kg body weight)
1	111	Overalls	101·9	76	74·9
2	132	Overalls	102·4	80	84·3
3	132	Shorts	100·8	71	74·0
4	150	Shorts	101·5	82	84·3

TABLE 111

Series IX. The effect on rectal temperature, pulse rate and sweat loss of exposing men for two periods of four hours in the one day to the same hot environment (dry-bulb 110°F, wet-bulb 88°F, air speed 150 ft./min)

Time	Rectal temperature (°F)		Pulse rate (beats/30 sec)	
	9 a.m. to 1 p.m.	5 p.m. to 9 p.m.	9 a.m. to 1 p.m.	5 p.m. to 9 p.m.
Initial	98·6	99·4	47	50
After Work I	100·1	100·9	63	73
After Rest I	99·7	100·5	50	54
After Work II	100·3	101·3	66	74
After Rest II	99·7	100·4	52	52
After Work III	100·4	101·1	68	68
After Rest III	99·5	99·9	50	50
After Work IV	100·0	100·5	67	53

Sweat loss (g/kg body weight)

9 a.m.–1 p.m.: 59·32
5 p.m.–9 p.m.: 60·80

TABLE 112

Series IX. The effect on rectal temperature and pulse rate of exposing men for three periods of four hours in the one day to the same hot environment (dry-bulb 115°F, wet-bulb 87°F, air speed 150 ft./min)

Time	Rectal temperature (°F)			Pulse rate (beats/30 sec)		
	9 a.m. to 1 p.m.	5 p.m. to 9 p.m.	1 a.m. to 5 a.m.	9 a.m. to 1 p.m.	5 p.m. to 9 p.m.	1 a.m. to 5 a.m.
Initial	98·6	99·8	99·1	44	49	47
After Work I	100·4	101·7	100·9	63	67	72
After Rest I	100·1	101·6	100·8	53	55	54
After Work II	101·0	102·2	101·5	66	71	70
After Rest II	100·3	101·6	100·8	51	54	58
After Work III	101·1	102·0	101·4	72	69	73
After Rest III	99·9	100·7	100·1	55	54	58
Final	100·6	100·3	100·8	70	70	73

TABLE 113

Series IX. Time (minutes) for which nine men, sitting at rest and stripped to the waist, were able to tolerate three excessively warm climates with average air speed 150 ft./min

Subject	Exp 1	Exp 2	Exp 3
	Dry-bulb 99·4°F Wet-bulb 99°F	Dry-bulb 130°F Wet-bulb 105°F	Dry-bulb 130°F Wet-bulb 100°F
1	135	39	34
2	134	38	39
3	250	55	129
4	136	30	48
5	137	36	55
6	132	37	38
7	110	33	36
8	185	33	42
9	79	33	78
Mean	144*	37	55

* Includes the value for subject 3 who was under severe stress, but not incapacitated, at the end

TABLE 114

Series IX. Rectal temperatures and standing pulse rates of the subjects of Table 113, recorded just before they left the warm environments

Subject	Expt 1 Dry-bulb 99·4°F Wet-bulb 99°F		Expt 2 Dry-bulb 130°F Wet-bulb 105°F		Expt 3 Dry-bulb 130°F Wet-bulb 100°F	
	Rectal temp. (°F)	Pulse rate (beats/30 sec)	Rectal temp. (°F)	Pulse rate (beats/30 sec)	Rectal temp. (°F)	Pulse rate (beats/30 sec)
1	101·7	74	102·4	70	101·4	65
2	101·4	63	102·2	64	101·6	77
3	101·4**	63	103·7	76	103·5	72
4	102·0	74	101·8	72	102·2	*
5	101·6	73	102·4	*	102·2	70
6	101·7	61	103·4	64	101·7	78
7	101·4	73	102·3	*	101·8	*
8	101·7	72	102·3	*	101·6	73
9	101·1	78	102·4	*	102·6	*

* Pulse rate of 80 beats/30 sec or more
** Subject 3 was not incapacitated

TABLE 115

Series IX. Endurance times, rates of rise of rectal temperature, rates of drinking cool water and rates of sweating for nine men in two climates

Experiment 1
(Dry-bulb 99·4°F, wet-bulb 99°F)

Subject	Endurance time (min)	Rate of rise of rectal temperature (°F/min)	Rate of drinking cool water (g/min)	Rate of sweating (g/min)
1	135	0·0265	20·4	17·5
2	134	0·0252	18·7	22·8
3*	240	0·0133	31·3	17·5
4	136	0·0256	16·5	24·1
5	137	0·0245	20·1	21·7
6	132	0·0248	20·8	20·2
7	110	0·0252	13·6	20·4
8	182	0·0176	24·7	31·1
9	79	0·0315	12·7	19·1

* This subject survived for the full 4 hr and completed 10 min step-climbing at the end of the experiment

Significant relations

Rate of drinking and endurance time: $r = -\cdot 96$ ($P = \cdot 001$)
Rate of rise of rectal temperature and endurance time: $r = -\cdot 97$ ($P = \cdot 001$)
Rate of rise of rectal temperature and rate of drinking: $r = -\cdot 91$ ($P = \cdot 001$)

Experiment 3
(Dry-bulb 130°F, wet-bulb 100°F)

Subject	Endurance time (min)	Rate of rise of rectal temperature (°F/min)	Rate of drinking cool water (g/min)	Rate of sweating (g/min)
1	34	0·0792	29·4	Not weighed
2	39	0·0812	32·1	28·9
3	129	0·0360	33·9	28·6
4	48	0·0720	26·0	23·7
5	55	0·0684	40·9	27·3
6	38	0·0781	32·9	23·2
7	36	0·0824	34·4	Not weighed
8	42	0·0779	47·6	34·3
9	98	0·0383	43·4	27·0

Significant relation

Rate of rise of rectal temperature and endurance time: $r = -\cdot 98$ ($P = \cdot 001$)

TABLE 116

Series IX. Survival times, sweat output and water intake for Subjects 10 and 11 for different climate and clothing combinations (air speed 150 ft./min)

S_{10} = Subject 10 S_{11} = Subject 11

Expt.	Dry-bulb temp. (°F)	Wet-bulb temp. (°F)	Clothing	Survival time (min)		Sweat loss (g/min)		Water intake (g/min)	
				S_{10}	S_{11}	S_{10}	S_{11}	S_{10}	S_{11}
4	130	100	Shorts	66	54	26·9	25·6	28·4	46·3
5	130	100	Shorts	77	61	31·1	25·1	18·2	24·6
6	130	95	Shorts	168	120	24·1	21·2	9·5	15·8
7	130	100	Overalls	93	52	34·1	27·7	26·9	34·6
8	99	97	Shorts	240	240	19·3	17·6	11·7	15·8

Tables to Chapter 9

TABLE 117

Values of the mean radiant temperature obtained with standing and sitting models in various positions and the values obtained with globe-thermometers at heights of 2 ft., 3 ft. 9 in. and 5 ft. 6 in. in the same positions

Mean radiant temperature obtained with globe-thermometer (°F)				Mean radiant temperature obtained with metal models (°F)	
At heights of			Average	Standing	Sitting
2 ft. 0 in.	3 ft. 9 in.	5 ft. 6 in.			
96·0	95·9	95·1	95·7	—	95·1
103·2	101·5	99·9	101·5	—	100·7
109·0	106·0	104·5	106·5	—	106·4
110·0	109·6	108·4	109·3	—	110·4
109·6	109·8	110·1	109·8	—	110·4
122·0	119·6	119·4	120·3	—	120·1
117·5	116·3	115·6	116·5	115·3	—
115·0	114·2	114·4	114·5	115·7	—
115·8	116·2	114·6	115·5	115·8	—
124·8	120·4	121·9	122·4	120·8	120·6
122·2	120·8	118·4	120·5	120·7	—
119·6	120·2	118·7	119·5	120·7	—
126·2	126·6	126·2	126·3	126·2	126·3
125·2	124·6	123·7	124·5	126·2	—
126·4	125·6	124·5	125·5	126·1	—

TABLE 118

Measurements of radiant heat. Results of experiments on standing and sitting models showing the amounts of radiant heat which would be gained by a black body in the same position and at the same temperature. All experiments conducted at dry-bulb 110°F, wet-bulb 87·5°F

Mean temperature of black model (°F)	Mean temperature of panels (°F)	$(\text{m.r.t.})^4 - (\text{model temperature})^4$ (°F abs. $\times 10^{-9}$)	Radiant heat gained by model (watts)
Standing model			
129·9	208·9	25·2	141
129·4	192·4	17·4	117
129·2	194·5	18·6	110
122·6	168·9	12·3	92
119·6	153·3	8·1	55
117·9	141·5	5·0	30
115·2	129·5	2·6	10
115·8	129·6	2·2	7
Sitting model			
127·0	205·3	25·7	113
125·3	187·9	18·6	105
122·2	168·2	12·0	77
121·4	172·1	14·5	69
122·6	152·4	5·5	18
115·2	129·5	2·6	7
118·9	130·3	0·1	−5
114·8	122·8	0·6	−8

TABLE 119

Thermal comfort on mess-decks. The effect of dry-bulb temperature on comfort sensation

m.t.w. = much too warm; t.w. = too warm; c.w. = comfortably warm;
c. = comfortable; c.c. = comfortably cool; t.c. = too cool

Dry-bulb temperature range (°F)	Total number voting	Percentage of voters who were						Percentage who were sweating	Percentage stripped to waist
		m.t.w.	t.w.	c.w.	c	c.c.	t.c.		
94·0 – 94·9	39	64·1	35·9	0	0	0	0	92·3	100·0
93·0 – 93·9	109	20·2	60·6	18·3	0·9	0	0	65·1	100·0
92·0 – 92·9	291	15·5	67·7	15·1	1·4	0·3	0	69·1	100·0
90·0 – 90·9	254	12·6	57·5	27·2	2·4	0·4	0	72·0	100·0
89·0 – 89·9	103	7·7	55·3	33·0	3·9	0	0	50·5	100·0
88·0 – 88·9	35	11·4	34·4	45·7	8·6	0	0	37·2	100·0
87·0 – 87·9	277	9·0	31·0	49·1	9·7	1·1	0	42·6	89·9
86·0 – 86·9	181	1·1	26·0	50·3	21·5	1·1	0	33·7	92·3
85·0 – 85·9	132	0	9·1	50·8	36·4	3·8	0	12·1	59·1
84·0 – 84·9	124	0	6·5	46·8	36·3	10·5	0	12·9	42·7
83·0 – 83·9	88	0	5·7	38·6	48·9	6·8	0	12·5	54·5
82·0 – 82·9	53	0	3·8	30·1	52·8	13·2	0	0	75·5
81·0 – 81·9	54	0	1·9	29·6	57·4	11·2	0	5·6	33·3
77·0 – 77·9	89	0	0	9·0	43·8	44·9	2·2	0	26·5

TABLE 120

Thermal comfort on mess-decks. The thermal comfort zone

	Expt.	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Effective temperature (°F)
Less than 20 per cent of voters were in the comfort zone* when the temperature was above:	1	91	82	84
	2	91	82	83
More than 50 per cent of voters were in the comfort zone* when the temperature was below:	1	89	81	82
	2	88	80	80
More than 80 per cent of voters were in the comfort zone* when the temperature was below:	1	86	80	80
	2	85	76	79

* Comfort zone: comfortable, comfortably cool, or comfortably warm

TABLE 121

Thermal comfort on mess-decks. Temperatures at which there was evident sweating on the face or chest

	Expt.	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Effective temperature (°F)
Less than 20 per cent of voters noticed sweating when the temperature was below:	1	86	80	79
	2	84	76	78
More than 50 per cent of voters noticed sweating when the temperature was above:	1	89	81	82
	2	88	79	79
More than 80 per cent of voters noticed sweating when the temperature was above:	1	94	84	85
	2	90	82	81

TABLE 122

Thermal comfort in warm and humid atmosphere. Acceptable levels of warmth for groups of European (E) *and Asian* (A) *men and women in Singapore*

	Group	Dry-bulb temperature (°F)		Wet-bulb temperature (°F)		Effective temperature (°F)	
		Men	Women	Men	Women	Men	Women
Upper limit of comfort zone: Over 80 per cent of voters were reasonably comfortable when the temperature was below:	E	84	82	79	76	79	78
	A	85	85	80	78	81	80
Lower limit of comfort zone: Over 80 per cent of voters were reasonably comfortable when the temperature was above:	E	76	76	74	75	73	72
	A	76	79	73	75	71	76
Less than 20 per cent of voters were 'wet' or 'clammy' when the temperature was below:	E	81	80	76	76	76	76
	A	82	83	76	77	77	79
Less than 20 per cent of voters were 'wet' with perspiration when the temperature was below:	E	87	83	80	78	80	80
	A	86	89	80	80	80	82

TABLE 123

Salt concentration and evaporation rate. The effect of concentration on the amount of water evaporated from sodium chloride solutions of varying concentration under standard conditions

Concentration of solution			Mean rate of evaporation (g/day)
Per cent saturation	Mols NaCl/1000g H_2O	g NaCl/1000 ml. of solution	
0	0	0	1·016
20	1·13	64	0·822
40	2·29	128	0·619
60	3·54	192	0·408
80	4·88	256	0·200
100	6·28	320	0·028

APPENDIX. EXPERIMENTS IN A TEMPERATE CLIMATE ON MEN ARTIFICIALLY ACCLIMATIZED TO HOT ENVIRONMENTS

An account of work done at The National Hospital for Nervous Diseases, Queen Square, London, 1944–1946 *by R. S. Benson, T. Colver, W. Dunham, H. E. Holling, W. S. S. Ladell, B. McArdle, J. W. Scott, M. L. Thomson and J. S. Weiner under the direction of E. A. Carmichael*

Ability to Work in Severe Heat

It has been pointed out that at its first meetings in 1944 the Ventilation Subcommittee of the Royal Naval Personnel Research Committee made two important decisions (Chapter 1). The first was that the Effective Temperature Scale should be used as the measure of environmental stress, and the second was that 80°F on the Effective Temperature Scale should be accepted provisionally as the level at which a significant decrease in the efficiency of a ship's company might be expected.

The Effective Temperature Scale, however, since its introduction in 1923 had not been without criticism. (That it had certain shortcomings was accepted by the workers who had originally devised the scale.) Furthermore, little was known of the effects on working efficiency of prolonged exposure to high temperatures. The research on the effects of environmental warmth conducted under the direction of the Subcommittee was therefore directed towards determining, firstly, whether the Effective Temperature Scale did constitute an acceptable measure of environmental warmth and secondly, whether the provisional level of 80°F on this scale was wisely chosen.

The task of measuring the psychological aspects of the effect of high environmental temperatures was undertaken by Dr. N. H. Mackworth at Cambridge. The workers at the National Hospital for Nervous Diseases, Queen Square, London, set about measuring the physiological effect and reported the greater part of their work in three important papers in 1945, 1946 and 1947.

The first of these papers, 'Ability to work in severe heat' (Benson *et al.*, 1945), gave an account of the first part of the work, the objects of which were to determine in relation to men working in magazines and cordite handling rooms:

1. The validity of the Effective Temperature Scale at high levels of temperature and humidity.
2. The upper limits of temperature and humidity at which their tasks could be efficiently performed.
3. The comparative value of measures for improving their efficiency.

METHODS

The experiments were conducted in the two air-conditioned rooms which had been built by the Admiralty at the National Hospital.

Experimental Routine

A conventionalized representation of men working in the magazines and cordite handling rooms of ships was chosen as the experimental routine. This routine simulated, by means of step-climbing, the work done in the cordite handling rooms and magazine of a 15-inch gun in a naval action lasting half an hour, followed, after an interval of 3 hr, by another engagement also lasting half an hour, at a rate of fire of 40 rounds in each half-hour period. The energy expenditure of men whilst working under such conditions had been calculated (Gray, 1945) to be approximately 400 kcal.hr^{-1}. The energy expenditure while step-climbing in the laboratory routine was found to be 380 kcal.hr^{-1}, which represented a very reasonable approximation to the expenditure in actual battle conditions. The laboratory routine was as follows:

Time (min)	*Activity*
0– 10	Subjects enter chamber; weighed naked; don weighed clothing
10– 40	Step-climbing* ('1st work')
40–210	Rest seated
210–240	Step-climbing* ('2nd work')
240	Subjects weighed naked and leave chamber; clothes weighed

* Three periods of 5 min at 24 steps/min alternating with three periods of 5 min at 12 steps/min on stools 12 in. high.

In all, 64 experiments were performed. In some of these, variants of the above routine were used. In five experiments the work done in magazines and cordite handling rooms was more closely simulated. In these experiments there were two 21-min work periods when men, every 45 seconds, lifted a dummy charge weighing 108 lb from a rack and, having carried it 14 ft., placed it in another rack. These work periods, from 10–31 min and from 210–231 min, were separated by a rest period of 179 min. The average energy expenditure of the men when working was 375 kcal.hr^{-1}. In order to compare the results of these experiments with those of others in which the work done was step-climbing, five experiments were performed in which two 20-min periods of step-climbing were substituted for the 30-min periods in the standard routine, with an intervening rest period of 190 min. In a further four experiments the first work period was omitted; the subjects sat from 0 to 210 min and then step-climbed for 30 min.

Control of Environmental Conditions

A shielded Assmann psychrometer, read every 5 min, was used as a check on the control of temperature and humidity. Temperature control was usually within less than 1°F of the desired value, but the humidity was less well controlled, and it is impossible to state just what degree of accuracy was attained in these earlier observations. Globe-thermometer readings were taken in the room and usually these did not differ appreciably from the corresponding dry-bulb temperature readings, except that at 120°F the globe-thermometer would read below air temperature.

In this first series of experiments the only control of air speed was that provided by varying the speed of the circulating fan. The air speed in the room was not uniform, but the subjects were carefully positioned so that they should all be exposed to similar conditions of air movement. Measurements of air speed were made with a silvered katathermometer.

Subjects

The 16 subjects were all naval ratings who had volunteered for the task. Their physical characteristics were:

	Mean	*Range*
Age (yr)	23·5	20– 32
Height (cm)	171·0	164–178
Weight (kg)	66·0	57– 74
Surface area (m^2)	1·77	1·64–1·88

Experimental Procedure

Two types of clothing were worn in the experiments. The first, briefly described as 'shorts', consisted of white cotton drill shorts and canvas shoes with light rubber soles. The second, known as 'anti-flash gear', consisted of a single-piece blue drill overall worn over a pair of shorts, together with anti-flash helmet, mask, anti-flash gloves, socks and the same canvas shoes. When the subjects were 'working' the legs of the trousers were tucked into the socks and the overall was completely buttoned up, but it is important to note that during the rest period the helmet and gloves were not worn, the overall was unbuttoned and widely opened, and the trouser-legs were frequently rolled up.

Unlimited but measured amounts of water at a temperature of approximately 60°F were allowed, and the subjects were encouraged to drink. Nevertheless, at the end of the four-hour experiment there was usually a water deficit of 1 to 2 litres.

Pulse rates and rectal temperatures were measured at intervals and sweat losses were calculated from weight changes. (A litre of sweat was assumed to weigh one kilogram.) An assessment of the physical state of each subject, based on the feelings of the subject and on the judgment of the observer, was also made for each experiment. The assessments were graded as follows:

1. Perfectly able to continue work.
2. Able to finish work and still efficient, but doubtful whether efficiency could be maintained for a further 10 min.
3. Able to finish work, but work done inefficiently.
4. Unable to finish work.
5. Collapse.

This assessment was described as the subject's 'Fitness Index'.

Acclimatization

Before commencing the experiments proper the subjects were acclimatized to hot environments by working for 4 hr per day for three weeks at a dry-bulb temperature of 100°F and a wet-bulb temperature of 94°F, the work being adjusted so that their rectal temperatures were maintained between 101°F and 102°F for about 2 hr.

RESULTS

Validity of the Effective Temperature Scale in Severe Heat

The experiments may be divided into two groups, the first performed to demonstrate the effects of varying the temperature and humidity while keeping the air speed constant at approximately 75 ft./min, and the second to demonstrate the effect, at chosen levels of temperature and humidity, of changes in air speed.

The Effect of Variations in Temperature and Humidity

It was concluded by the authors that for the conditions of their experiments, it would not have been possible to forecast from the Effective Temperature Scale the reactions of the subjects at any given combination of temperature and humidity. This applied both when they were working for half an hour at 380 kcal.hr^{-1} and when they were resting for 3 hr after such work. It applied, too, both when they were wearing shorts and when they were wearing anti-flash clothing.

This statement was based in particular on the results of Expt. 5, 6 and 7 (Table 1A) in which the effects of three different environments having the same effective temperature are compared. It was claimed that the lower the wet-bulb temperature the better was the performance of the subjects. All eight men were thoroughly fit when the wet-bulb temperature was 83·55°F, but three of the eight men became inefficient when it was 91·0°F. The general conclusion of the authors was that for the conditions of clothing, work and environment obtaining in these experiments the Effective Temperature Scale over-estimates the effect of the dry-bulb temperature.

Further support for this conclusion was found in the results set out in Table 2A where the results of pairs of experiments are contrasted. One experiment of each pair was conducted in a hot dry environment (Expt. 10, 11, 30, 36 and 37), and one in a hot wet environment (Expt. 3, 9, 26, 34 and 35). In each case the effective temperature of the hot wet environment was some 2°F lower than that of the corresponding hot dry environment and yet the strain produced by the hot dry environment was considered to be less than that produced by the hot wet environment; this appeared to apply whether the subjects were wearing anti-flash clothing or only shorts.

The results of a further two pairs of experiments (Expt. 39 and 40, and 41 and 42), are quoted in Table 3A to show the relative effects of hot dry and hot wet environments with the same effective temperature on men while they were working and while they were resting. In these experiments a variation in the routine previously followed (p. 281) was used. The men rested in the given environment for 210 min and then step-climbed for 30 min. The reactions of the men in each pair of experiments while resting were considered to be very similar, and therefore the results were said to be in accordance with the Effective Temperature Scale, but the rise in rectal temperature during work was greater in the hot wet environments both for men in shorts and for men in anti-flash clothing, and the fitness rating after work was decidedly inferior in the hot wet environment for men wearing anti-flash clothing.

The Effect of Variations in Air Speed

The effect of varying the air speed in hot wet and hot dry environments was examined both for men wearing shorts and for men wearing anti-flash clothing. The air speeds used ranged from '10 ft./min' to '200 ft./min' but the values quoted can be considered as nominal. The observed values, which varied from place to place within the chamber, were:

Nominal value	*Observed values*	
	Resting position (mean values)	*Working position (mean values)*
10	10	10
50	45	25
75	70	55
125	125	75
200	220	95

Subjects wearing anti-flash clothing in hot wet environments. The results of the experiments in these conditions are exemplified in Table 4A. These show that the severity of conditions at very low air speeds (10 ft./min) can be greatly diminished by a small increase (for example to 75 ft./min) in the air speed.

The improvement resulting from a further increase in air speed (up to 200 ft./min) is, however, much less marked. These effects are not accurately represented by the values assigned to the several environments on the Effective Temperature Scale. Fig. 1A illustrates the behaviour of the mean rectal temperature of the subjects in these experiments, and further demonstrates the greater severity of the same conditions of temperature and humidity at very low air speeds. The rectal temperature continued to rise for 15 min after the end of the first work period when the air speed was 10 ft./min, but at 75 ft./min it ceased to rise at the end of the work period. During the period of rest the rectal temperature fell much more slowly at 10 ft./min than at 75 ft./min. The figure also shows that the improvement effected by increasing the air speed beyond 75 ft./min was not so marked as the improvement effected by increasing the air speed from 10 to 75 ft./min. The authors concluded—'It is thus apparent that the Effective Temperature Scale tends to under-estimate the deleterious effect of still air in hot humid conditions or fails to recognize fully the beneficial effects of increasing the air speed'.

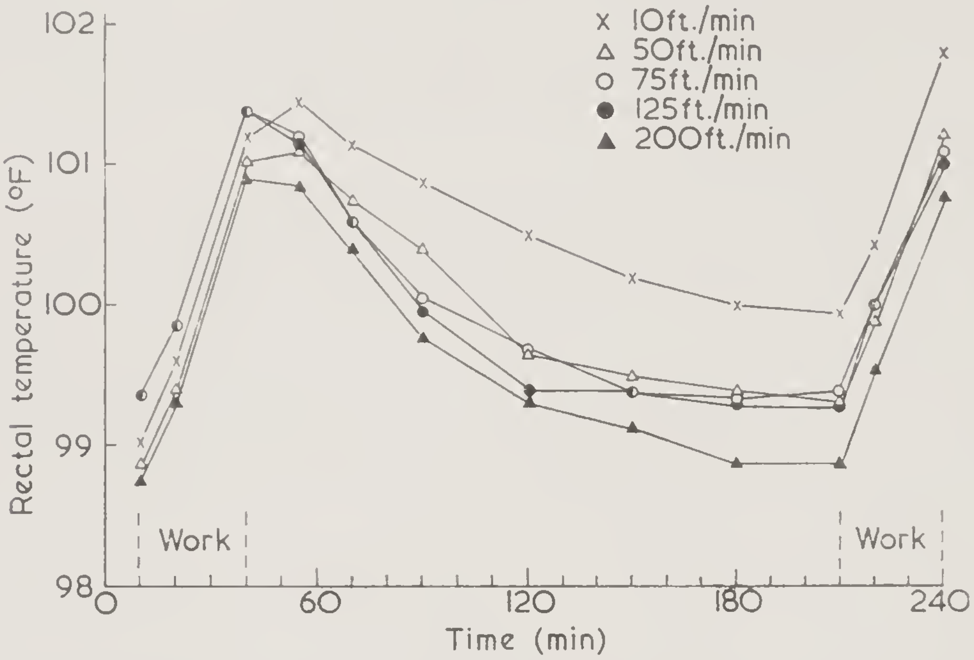

FIG. 1A. The effect of different air speeds on the rectal temperature of men wearing anti-flash clothing in experiments at dry-bulb temperature 92°F, wet-bulb temperature 90°F.

Subjects wearing shorts in hot wet environments. The results of these experiments are exemplified in Table 5A, which shows the effect of increasing the air speed from 10 ft./min to 200 ft./min in air which is almost saturated at a temperature of 90°F. Increasing the air speed from 10 ft./min to 75 ft./min did produce an improvement in conditions, but it was considered that this improvement was not so marked as in the case of men wearing anti-flash clothing, and was adequately represented by the Effective Temperature Scale.

Subjects wearing anti-flash clothing in hot dry environments. It was not found possible to control the temperature and humidity in hot dry environments satisfactorily at an air speed of 10 ft./min, so that the lowest air speed used in experiments in these environments was 50 ft./min. The results of a series of experiments at dry-bulb 120°F, wet-bulb 88°F, are set out in Table 6A. Increasing the air speed from 50 ft./min to 125 ft./min, or to 200 ft./min, did not produce a marked improvement in conditions, and the authors concluded that for men in anti-flash clothing the effects of increasing the air movement are less striking in hot dry than in hot humid conditions.

Subjects wearing shorts in hot dry environments. The results of two pairs of experiments at air speeds of 75 ft./min and 200 ft./min are quoted in Table 7A. It was concluded from these experiments that 'the effect of increasing the air movement in hot dry conditions on subjects clad in shorts is negligible.'

The general conclusion drawn from the experiments in hot dry environments was that 'If the results so obtained, both when anti-flash and when shorts are worn, are studied in relation to the Effective Temperature Scales, it is found that the slight effects of increasing air movement are in keeping with the physiological response that might be predicted from the Effective Temperature Scale.'

Limiting Environments for Men in Magazines

A series of five experiments was performed in which the work done in cordite handling rooms and magazines was closely simulated (p. 281). In these experiments the two periods of work were approximately 20 min each and not 30 min as in the previous step-climbing experiments. A further series of five experiments with 20 min periods of step-climbing was also performed. The results of the ten experiments are set out in Table 8A, together with those of Expt. 64, in which the step-climbing period was 30 min, which was performed in order to demonstrate, by comparison with Expt. 63, the added stress of the further 10 minutes' work in the standard experiments. Examination of the first two pairs of experiments in Table 8A will show that the results for step-climbing are very similar to those for loading, although the authors make the point that the men loading became somewhat more inefficient towards the end of the experiment owing to tiring of the muscles of the back and arms.

Based on the results of these experiments and the step-climbing experiments previously described, Table 9A was drawn up to show the 'upper tolerable levels' of wet-bulb temperature in saturated atmospheres and at an air temperature of 120°F, at various levels of air speed, for two types of clothing, for loading and step-climbing, and for 20 min and 30 min work periods. The criterion used in determining these values was that not more than 10 per cent of the men concerned should be considered to be inefficient or of doubtful efficiency. This corresponded in these experiments with a rectal temperature of 101°F and a pulse rate of 150–160 beats/min at the end of the second period of work, a sweat loss of 4–4·5 litres in the four-hour period and a fitness index of 1·6–1·7. The subjects usually had a water deficit of 1·5 litres at the end of the experiment. At an air temperature of 120°F the sweat losses were usually 500–1.000 g greater for the four-hour period than in the near-saturated environments.

The general conclusion was drawn that most fit acclimatized men in hot saturated environments could tolerate wet-bulb temperatures up to 90°F except when they were clad in anti-flash clothing and the air speed was reduced to 10 ft./min. At an air temperature of 120°F men were able to tolerate wet-bulb temperatures up to 88°F.

DISCUSSION AND CONCLUSIONS

In the discussion of the results it was pointed out that the conclusions with regard to the accuracy of the Effective Temperature Scale were in general agreement with the findings of other workers in America. These conclusions were that for 'resting' men the Effective Temperature Scale can provide an accurate measure of the thermal stress of the environment, but that for 'working' men, or men resting after work, the scale is inaccurate, in as much as it over-stresses the importance of the dry-bulb temperature and under-emphasizes the relative importance of the wet-bulb temperature. Furthermore, in hot humid environments 'still' air was found to produce a much greater physiological strain than that indicated by the Effective Temperature Scale.

The application of these results, obtained from the study of men who spent only 4 hr per day in the hot room and the remaining 20 hr in a temperate climate, to men living and working in the tropics presented considerable difficulties. It was thought that whereas the general conclusions concerning the Effective Temperature Scale as a measure of heat stress might apply equally well in the tropics, the limiting environmental conditions might well be different from those observed in the course of the experiments.

This, clearly, was an important point, and it was concluded that the experimental subjects might well have been both better acclimatized and better accustomed to heavy work than naval ratings who would be expected to undertake such tasks in the tropics. In this case, the values obtained for the limiting environments given in Table 9A would be too high. There was also to be considered the unknown effect on the ability of men to work in severe heat of cordite fumes and the high concentrations of carbon dioxide which might occur in ships' magazines. The inference was plain that these important questions could only be settled by observations on men living and working under tropical conditions.

In conclusion, the authors summarized the significance of their findings in relation to very hot environments as follows.

1. *The Effective Temperature Scale*

'In assessing the ventilation requirements of different compartments in ships, naval ventilating engineers are to some extent dependent on the Effective Temperature Scales. If the engineers continue to use these scales in an unmodified form it is not improbable that it might result in a faulty apportionment of fans or refrigerators, or that improved ventilation might be first installed in compartments having less need of it than others. Such faulty apportionment would be caused by (1) the over-emphasis given to the dry-bulb temperature by the Effective Temperature Scales in the case of men working in such compartments, and (2) the under-emphasis of the effects of still air on men working or resting after work in hot humid atmospheres.

2. *Anti-flash and Shorts*

'There can be no doubt from the results that there is a very notable increase in the ability of men in shorts to work in hot environments than when clad in anti-flash gear. This applies more particularly to hot humid environments with low air movements. Men working in magazines and cordite handing rooms are exposed to a saturated atmosphere and still air, and in such hot saturated conditions men clad only in shorts can tolerate temperatures about 3 F wet-bulb higher than men in anti-flash. It should be pointed out that at these temperatures, when every degree rise in wet-bulb temperature produces a marked increase in physiological strain, an increase of 3°F in the level of the limiting environment is a notable gain. It is probable that the wet-bulb temperatures that may be attained in such compartments in the Pacific may prove to be intolerable for men in anti-flash, but tolerable for men in shorts.

3. *General Reactions to Heat*

'The experiments also bring out the increased physiological strain at these high levels of temperature and humidity imposed by comparatively small increases in rate or duration of work; by a slight rise in wet-bulb temperature; or by a decrease in air movement.

4. *Limiting Environments*

'Until the state of acclimatization of our men has been compared with that of naval ratings in the tropics, and until the effects of CO_2 and cordite fumes on the ability to work in heat are known, no definite recommendations can be given as to the levels of the limiting environments for ships in tropical climates. It is improbable that the levels of the limiting environments for men in the tropics are higher than those given in Table [9A]. On the other hand, it is more probable that they are two or three degrees lower.'

The Effects of Air Movement in Severe Heat

The work just described drew the attention of the workers at the National Hospital to the effects of varying the air speed on the physiological response to hot environments. In view of the importance of the results obtained, it was considered necessary that a survey should be undertaken of the effects of air speed over a wider range than had previously been investigated. These experiments and their results were described in a paper entitled 'The effects of air movement in severe heat' (Dunham, Holling, Ladell, McArdle, Scott, Thomson and Weiner, 1946) and they form the subject of this section.

METHODS

The methods employed were essentially those used in the previous experiments but modified in certain important respects. In order to provide a wider range of air speeds than was previously available, a small wind tunnel was constructed inside one of the climatic chambers. Two 20-in. fans, placed one above the other, drew air through a corridor 7 ft. long, 5 ft. broad and 7 ft. in height occupying the long axis of the room. With this arrangement only two subjects could be used at a time, and the maximum air velocity obtainable was 500 ft./min. These conditions were unsatisfactory, and with the help of the National Physical Laboratory an improved arrangement was devised. A central partition was built along the long axis of the room and a partial false roof fitted so that the room was converted into a rectangular corridor 5 ft. wide and 7 ft. 3 in. in height with two long and two short sides. The two fans were placed in one of the shorter lengths of corridor and the air directed around the corner by means of baffles. Two subjects could sit or work in each of the two long sections of the corridor facing into the air stream. With this arrangement, air velocities of up to 800 ft./min could be achieved. At air speeds of up to 300 ft./min a fine gauze screen was placed immediately in front of each pair of subjects to provide a more uniform air flow. These screens, however, reduced the air speed to such an extent that at higher velocities they had to be omitted. Without them the air flow was much more turbulent and varied more from place to place throughout the tunnel.

The air speed at each of the positions occupied by a subject was measured with a silvered katathermometer. The observer sat in the position at which the air speed was to be measured, and other positions were occupied by subjects in the usual way. Measurements were made at some ten or twelve different positions, and it was found that the air speed varied considerably from place to place. For example, at a nominal air speed of 100 ft./min the head of the subject might be in an air stream with a speed of 120 ft./min whilst the air flow about his thighs might be 90 ft./min. Adjustments were made, therefore, so that the average air flow about the subject was the desired value. Even so, owing to the turbulence and other irregularities of air flow and variations in the position of the subject when sitting and step-climbing, the mean figures may have an error of as much as ± 20 per cent at low air speeds and ± 10 per cent at the upper end of the range.

Dry- and wet-bulb temperatures were measured with an Assmann psychrometer and, as before, control was usually within ±0·5°F. Globe-thermometer readings did not usually differ from the air temperature reading except at 120°F when they might be as much as 1°F less.

The effects of two levels of energy expenditure were investigated. At the lower level ('resting'), the men remained seated in chairs throughout the four-hour period except at such times as they were donning or removing their clothing, being weighed, or having their pulses counted or their temperatures taken. At the higher level ('working'), the men alternately rested in chairs and step-climbed on stools 12 in. high 12 times per minute. In detail this second routine was as follows:

Time (*min*)	*Activity*
0– 10	Subjects enter chamber; weighed naked; don weighed clothing
10– 40	Step-climbing
40– 70	Rest, seated
70–100	Step-climbing
100–130	Rest, seated
130–160	Step-climbing
160–220	Rest, seated
220–240	Step-climbing
240	Subjects weighed naked and leave chamber; clothes weighed

When the subjects were resting they usually sat in the chairs provided, but sometimes they sat on their stools. While sitting they amused themselves variously, usually reading or talking, occasionally playing cards, and sometimes they slept. The energy cost of the activities was measured by the usual method of indirect calorimetry, and is quoted as being 54 kcal.m^{-2}.hr^{-1} for the men when resting and 180 kcal.m^{-2}.hr^{-1} when step-climbing. The average energy expenditure in those experiments described as working was, when allowance was made for the time spent sitting and step-climbing, 111 kcal.m^{-2}.hr^{-1}.

The experimental routine for working subjects just described is basically that used in the previous series of experiments. It has been modified somewhat in order to distribute the energy expenditure more evenly throughout the four-hour period, but the relation to the original routine designed to simulate conditions in a ship's magazine is clearly apparent. It has been described at some length as it was used extensively in later experiments at Singapore, and came to be known as the 'Queen Square Routine' for 'working' men.

Rectal temperatures and the 'standing' pulse rates were taken at intervals throughout the experiments. Sweat loss was estimated from differences in weight, and the amount of sweat evaporated was calculated by subtracting that which remained in the clothes from the total loss, when lack of dripping made this possible. The scale for assessing the 'fitness' of working subjects was changed slightly from that used in the previous experiments (p. 282), in that a new grade 'O — unaffected by work and heat' was inserted, and in that intermediate points between the grades were used. The comfort of subjects in the 'resting' experiments was assessed. They were asked whether they considered the environment to be 'very good' (with a numerical rating of 5), 'good' (4), 'fair' (3), 'bad' (2), 'very bad' (1) or intermediate between any two. This was referred to as the 'Comfort Rating'.

Two kinds of clothing were worn. The first was white drill shorts and rubber-soled canvas shoes. The second, which replaced the protective anti-flash gear of the previous experiments, consisted of a standard naval single-piece blue drill overall worn over shorts, together with the usual canvas shoes. The overall was usually partially unbuttoned.

An attempt was made to maintain the subjects in a relatively constant state of acclimatization by alternating exposures to hot dry environments with exposures to hot wet environments, and by classifying the experiments as 'severe', 'moderate' or 'mild', and arranging them so that two exposures of equal severity did not follow one another. The experiments were so allocated that in the first part of the series one half of the men alternated the arduous task of working in overalls with the relatively easy task of sitting in shorts, while the other half of the subjects alternated the two moderate tasks of working in shorts and sitting in overalls. In the latter part of the series the order was reversed. At approximately fortnightly intervals men who had taken part in the morning experiments changed to afternoon experiments, and vice versa. Subject to these restrictions the treatments were applied in a random order.

In all a total of 749 'man-experiments' were performed at air temperatures ranging from 82°F to 120°F in combination with a variety of humidities and air speeds. The results of all these experiments are quoted in appendices to the original paper, but the authors' conclusions are based chiefly on the results of 185 'man-experiments' which systematically examined the effects of different levels of air speed for men both working and resting, and both wearing shorts and wearing overalls, over the following range of temperature and humidity.

Dry-bulb temperature (°F)	*Wet-bulb temperature (°F)*	*Relative humidity (%)*	*Vapour pressure (mm Hg)*
120	83	22	18·5
120	88	28	25·0
100	83	49	24·2
100	88	62	30·5
90	83	75	27·0
90	88	93	33·5

Four levels of air speed were investigated. The actual values varied considerably from experiment to experiment (see Tables 10A–13A) but were roughly 30, 100, 300 and 500 ft./min, although in certain experiments the fourth level of air speed was as high as 800 ft./min.

The subjects used in these experiments were those used in the experiments described in the previous section.

RESULTS

The results of the shorter series of 185 experiments are set out in detail in Tables 10A–13A. From a study of these results the authors were of the opinion that the most reliable measure of the effect of any set of conditions was the rate of sweating, so that, although the heart rates and rectal temperatures were also measured and the fitness and comfort of the subjects assessed, the findings which are set out in this section are largely based on the measurement of the amount of sweat lost.

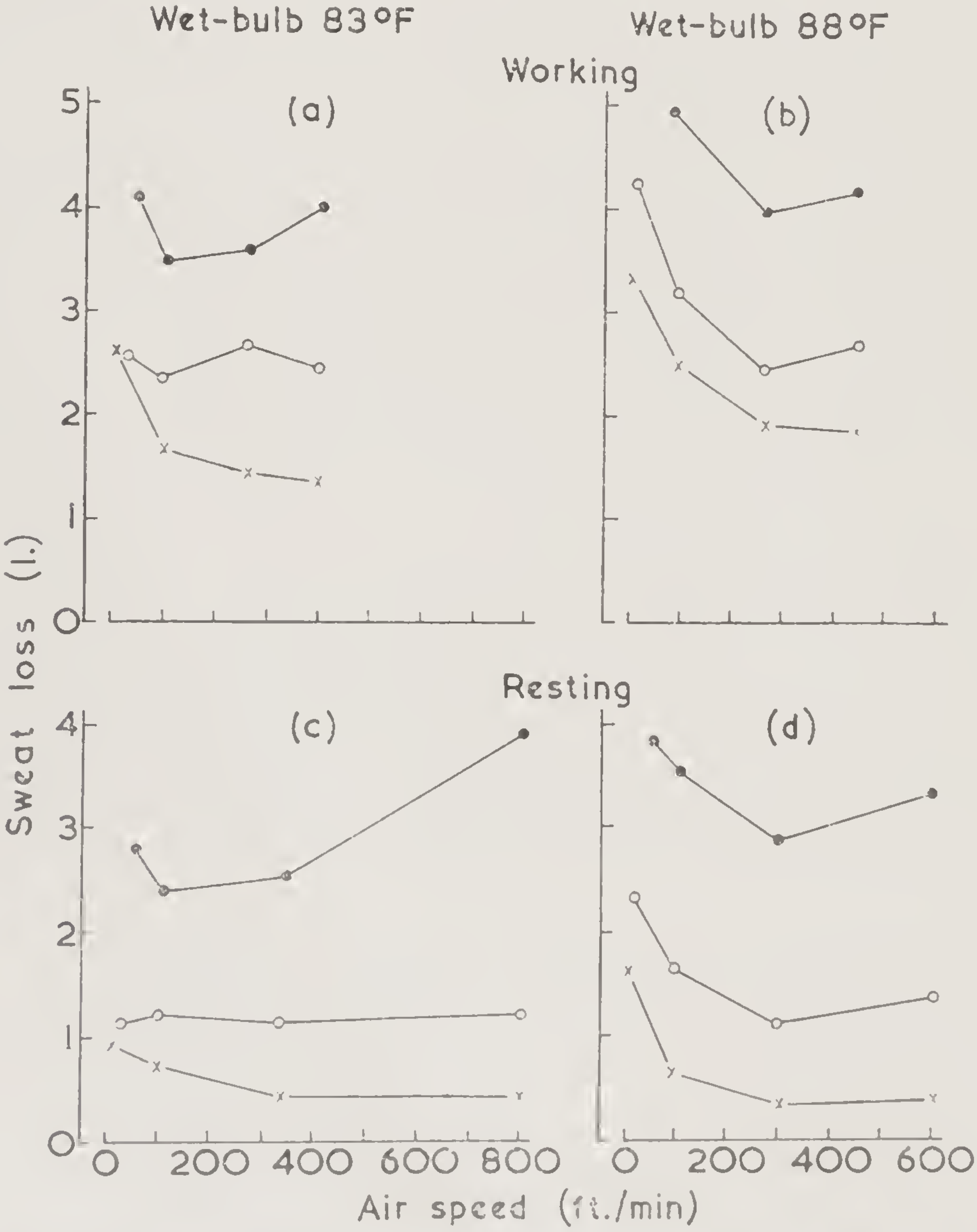

FIG. 2A. The effect of increasing the air speed on the mean sweat loss of men wearing overalls at three levels of air temperature—90 F( ), 100 F(O) and 120 F(●).

The Effect of Air Speed on the Sweat Loss

The effects of changes in the air speed on the amount of sweat lost are shown in Fig. 2A and Fig. 3A. Fig. 2A illustrates the effects for men wearing overalls resting and working at three air temperatures, 90°F, 100°F and 120°F, and two levels of humidity, wet-bulb temperatures of 83°F and 88°F. Fig. 3A similarly illustrates the effects for men wearing shorts over the same range of conditions. The same two men were the subjects in all the experiments on which Fig. 2A(a) and Fig. 2A(d) were based; another pair were the subjects in all the experiments referred to in Fig. 2A(b) and Fig. 3A(c), and there were two more pairs of subjects for the experiments of Fig. 2A(c) and Fig. 3A(b) and for Fig. 3A(a) and Fig. 3A(d). It should be noted that the range of air speeds covered is not the same in all cases and in particular that the lowest air speed obtainable varied with the temperature and humidity.

It can be seen from these figures, and especially from Fig. 3A(b), that the effect of increasing the air speed could in general be divided into two phases. The first phase was characterized by a fall in the rate of sweating but the extent

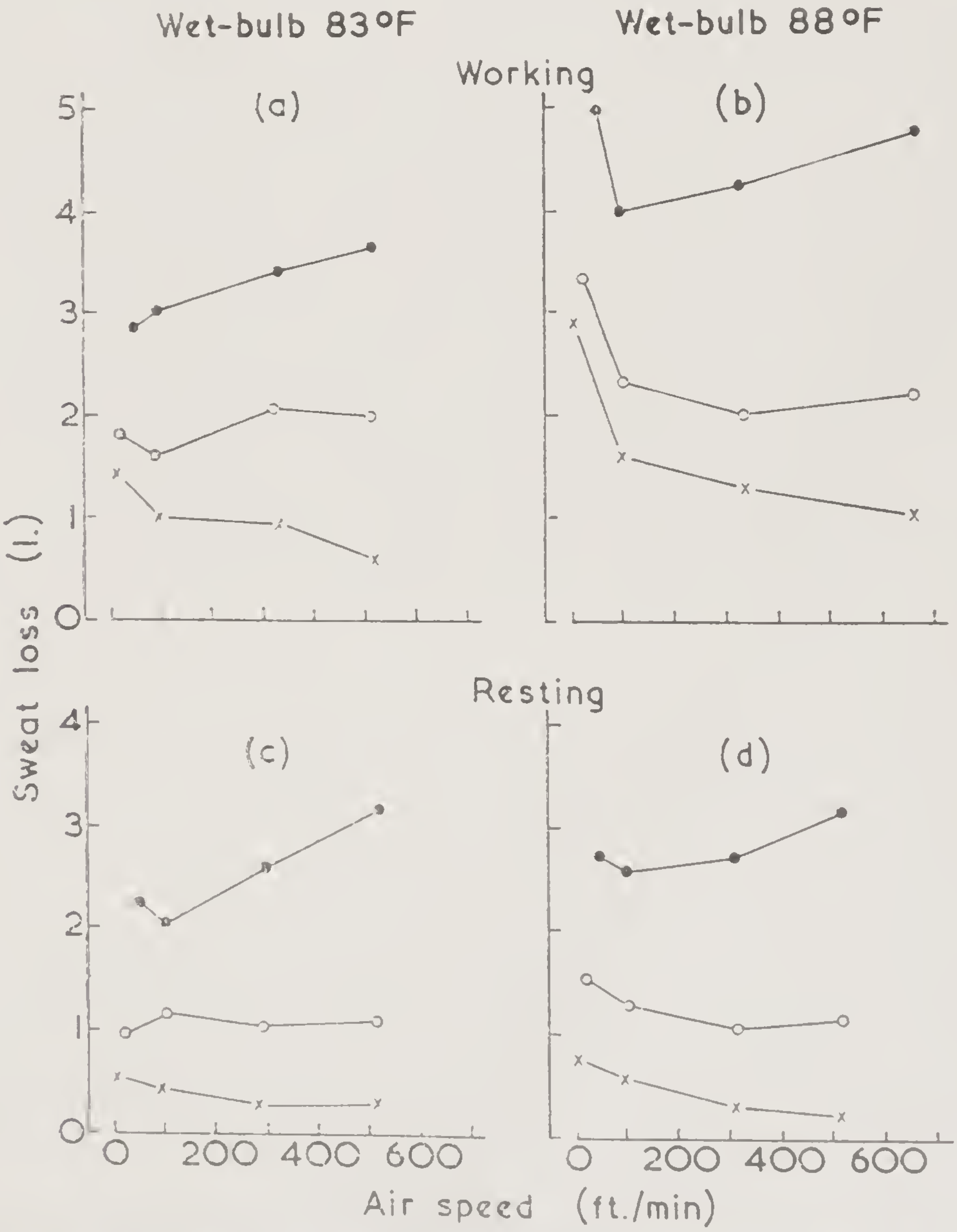

FIG. 3A. The effect of increasing the air speed on the mean sweat loss of men wearing shorts at three levels of air temperature—90 F( ), 100 F(O) and 120 F(●).

of this fall depended on the rate of energy expenditure, the clothing worn and the wet-bulb temperature. These same factors also determined the air speed at which the first gave place to the second phase. This second phase was characterized at an air temperature of 120°F by an increase, at 100°F by little or no change and at 90°F with a fall in the rate of sweating as the air speed was increased. At 90°F it was not always possible to make a distinction between the two phases—the fall in the first phase being continued into the second without noticeable inflection.

The existence of these two phases is to be explained by the twofold effect of increasing the air speed—greater evaporative cooling if the surface is moist, and greater convective heat gain or heat loss depending on the relative temperatures of the skin and air. In the first phase the increase in evaporative cooling was greater than the increase in convective heat exchange, and therefore the effect of increasing the air speed was in all cases to alleviate conditions. In the second phase the convective effect predominated over the evaporative and, at air temperatures above that of the skin, increasing the air speed resulted in an increasing quantity of heat which the body had to dissipate by the production of more sweat; at air temperatures below that of the skin, increasing the air speed resulted in increasing convective cooling and therefore a further alleviation of conditions.

The improvement in conditions which occurred during the first phase was greatest in the case of subjects wearing overalls and working at a wet-bulb temperature of 88°F (Fig. 2A(b)) and least in the subjects sitting in shorts at wet-bulb 83°F (Fig. 3A(c)). The more severe the conditions were in other respects, the more deleterious was the effect of low air speeds. For example, when the dry-bulb temperature was 120°F and the wet-bulb 88°F (Fig. 2A(b)) the two subjects, when working and wearing overalls, were unable to continue for more than 175 min and 210 min respectively when the air speed was 50 ft./min, but they were able to complete the full 4 hr of the experimental period when the air speed was 100 ft./min albeit with some difficulty. A further increase in the air speed to 275 ft./min resulted in a further improvement in conditions, the amount of sweat lost in the 4 hr decreasing by nearly 1 litre. On the other hand (Fig. 3A(c)), when the same subjects wearing shorts were sitting in an environment with an air temperature of 120°F and a wet-bulb temperature of 83°F their sweat loss fell by only 170 g in 4 hr when the air speed was increased from 50 to 100 ft./min, and rose by 567 g when the air speed was further increased to 240 ft./min. Furthermore, since the lowest air speed studied at 120°F was 50 ft./min and at 90°F was 10 ft./min, it was concluded from Fig. 2A(b) and Fig. 3A(c) that the higher the dry-bulb temperature the greater was the effect of increasing the air speed during this first phase.

The decrease in the amount of sweat lost which occurred during the first phase was almost entirely accounted for by the decrease in the amount of sweat remaining unevaporated in the clothes, and the transition from the first to the second phase was observed to occur at the point where the amount of unevaporated sweat ceased to decrease rapidly when the men wore overalls or where it almost disappeared in the case of men wearing shorts. The more severe the conditions of air temperature, humidity, work and clothing, the higher the air speed at which the transition occurred. Thus, for men working in overalls at dry-bulb 120°F, wet-bulb 88°F, the transition point was approximately 300 ft./min (Fig. 2A(b)) whereas for men sitting at rest in shorts at dry-bulb 120°F, wet-bulb 88°F, the transition point was 100 ft./min or less.

The effect of increasing the air speed in the second phase depended on the dry-bulb temperature. This is well shown in Fig. 3A(c). In these experiments, when the dry-bulb temperature was 120°F the fall in the amount of sweat lost which occurred in the first phase was followed in the second phase by a steady rise in the amount of sweat lost. At 100°F no consistent change was observed in the rate of sweating. At 90°F the characteristic fall during the first phase was continued in the second phase until it reached 50–100 g/hr, after which it remained steady. The point had presumably been reached at which sensible perspiration was negligible, the loss in weight being largely due to insensible perspiration and to carbon dioxide and water vapour lost in the breath.

In the case of men wearing shorts the amount of sweat remaining unevaporated in the clothing at the end of the first phase was very small, so that any further decrease in the amount of unevaporated sweat during the second phase was negligible. In the case of men wearing overalls, however, when the wet-bulb temperature was 88°F, there was still a considerable amount of unevaporated sweat in the clothing at the end of the first phase. During the second phase this amount was further reduced, but even at an air speed of 500 ft./min when the dry-bulb temperature was 120°F there was 300 g in the clothing of sitting men and 530 g in those of working men. In the same conditions, but at 83°F wet-bulb, the amount of sweat present in the clothing was less but still appreciable.

The Effect of Air Speed on Rectal Temperatures and Pulse Rate

The authors summarized their findings as follows. 'Changes in rectal temperature and pulse rate closely followed the changes in sweat rate, with two exceptions. Increasing the air movement at dry-bulb temperatures below 95°F resulted in a continuous fall in rectal temperature and pulse rate, even though sensible perspiration had become negligible. The rectal temperature of sitting subjects was found a less satisfactory index of environmental conditions than the sweat rate, owing to the day-to-day variability of the rectal temperature at the start of the experiment having a proportionately greater effect on the final rectal temperature when changes during the experiment were slight. In addition, a small change in rectal temperature is very much less easily measured than the equivalent change in sweat rate and, of course, the significance of fractional differences in rectal temperature is dubious when the error due to the thermometer may be ±0·2°F.'

The Effect of Air Speed on Comfort and Efficiency

It was found that 'It was not possible to obtain an accurate and sensitive measure of the subjective sensations of the men. In general they paralleled the physiological findings. Environments in which the air movement was less than 50–200 ft./min (depending on work, clothing and wet-bulb) were wholeheartedly disliked; and the subjects fully appreciated the extent to which, at these levels, a small increase in air movement improved their comfort and efficiency. To a rather less extent also the subjects disliked high air movements (over 200–300 ft./min, but depending on the work, clothing and wet-bulb temperature) when the dry-bulb temperature was high. They complained particularly that their eyes became dry and sore, and that their skin, especially of their face, was uncomfortably hot.'

DISCUSSION AND CONCLUSIONS

In the discussion of the results the authors emphasized the importance of the two phases in the effect of increasing the air speed and stressed that the decrease in sweat output in the first phase was largely accounted for by the decrease in the amount of unevaporated sweat present in the clothing. From this it was concluded that, except in certain special circumstances, it might be safely said that if unevaporated sweat is present in the clothes in areas fully exposed to the air stream, or if sweat is running off areas of skin similarly exposed, increasing the air movement will result in improvement. If, on the other hand, the clothes are dry or the skin only moderately moist, comparatively little improvement will result at dry-bulb temperatures below 95°F from an increase in the air speed, and at temperatures above 100°F an increase in the air speed will produce increased discomfort the extent of which will depend upon the amount by which the air temperature exceeds this value. It was also concluded that the most generally useful range of air speed for men working in tropical conditions is 100–150 ft./min when shorts only are worn and 150–300 ft./min when overalls are worn.

Air Speed and the Effective Temperature Scale

The previous work of Benson *et al.* (1945) had shown that the Effective Temperature Scale failed to emphasize sufficiently the deleterious effects of low air speeds on men working in hot environments. The present findings provided a much more exact measure of the extent to which the effects of variations in the air speed diverged from what would be predicted from the Effective Temperature Scale, and more especially of the failure of the scale to recognize the harmful effects of high air speeds at high air temperatures.

In Table 14A are set out the effects of varying the air speed on two men working in shorts at an air temperature of 120°F and a wet-bulb temperature of 88°F. The values assigned by the Effective Temperature Scale indicate a progressive improvement in conditions as the air speed is increased from 50 ft./min to 660 ft./min, whereas the sweat loss and rectal temperature clearly indicate at first a very marked improvement as the air speed is increased from 50 ft./min to 100 ft./min, and then a deterioration as the air speed is further increased.

Deleterious Effects of High Air Speeds in Hot Dry Environments

The authors considered that whereas excessive air speeds may not produce serious consequences in hot moist atmospheres, in dry atmospheres with very high air temperatures the results may be extremely harmful. Ladell, Waterlow and Hudson (1944) had shown that in very hot dry (desert) climates water and salt intakes were often not replaced in quantities adequate to meet the demands of the high rates of sweating which occurred under such conditions, and it was thought that any increase in these demands caused by an exacerbation of the conditions might predispose to heat stroke.

Prediction of the Physiological Effects of Warm and Hot Environments: The P4SR Index

The workers at the National Hospital (as a result of their experimental findings which have been described in the preceding sections) concluded that there was a real need for a new index to replace the Effective Temperature Scale. They considered that the Effective Temperature Scale, though it was useful and had been widely used, was in error in certain important respects. It over-emphasized the part played by the dry-bulb temperature as opposed to that of the wet-bulb temperature in contributing to the stress of hot environments. It failed to indicate sufficiently the very deleterious effects of 'still' air on men working in environments of high humidity. At high dry-bulb temperatures (above 100 F) it indicated, provided the wet-bulb temperature was not above 96 F, a continuous improvement with a rise in the rate of air speed instead of an improvement followed by deterioration. The Effective Temperature Scale had in addition, they considered, other shortcomings. It did not make allowance for sufficient variations in the amount of clothing worn—it provided only for men clad in light indoor clothing and men stripped to the waist.* It took no cognizance of the level of energy expenditure in assessing the stress of an environment, being designed for men at rest or engaged in light activity. Moreover no provision was made in the scale, as originally proposed, to include the effects of an increase or decrease in the mean radiant temperature. The modification of the scale which had recently been proposed by Bedford (1946) to include the effects of radiant heat (the Corrected Effective Temperature Scale) they considered 'based on theoretical considerations and awaits experimental proof'. Finally, the National Hospital workers considered it a disadvantage that the relationship between the effective temperature and physiological strain was not linear but curvilinear. (The increase in physiological strain produced by a given increase in effective temperature was much greater at higher than at lower levels of effective temperature.)

There had been, of course, numerous other attempts to devise scales of physiological effect. For example, Gagge, Herrington and Winslow (1937) had proposed a psychrometric chart on which were drawn contour lines representing the upper limits of evaporative regulation of body temperature. These contour lines did not, however, take into consideration the effect of work rate or the clothing worn, being devised for unclothed resting men, and from their very nature could not constitute a universal index of physiological effect. Robinson, Turrel & Gerking (1945) also had produced their 'Index of Physiological Effect', but the contour lines in this, although they related to three levels of metabolism and two levels of clothing (shorts and poplin uniforms), related only to one level of air speed, 180 ft./min.

In the view of the National Hospital workers, any new scale of environmental stress should clearly avoid the deficiencies described. It should represent correctly the effects of air temperature, humidity, radiant heat and air speed. It should embrace the effects of the level of energy expenditure and the amount of clothing worn. The environmental stress should be assessed in terms of the physiological strain produced, and the relationship between the unit of stress and the strain should be linear.

THE PREDICTED FOUR-HOUR SWEAT RATE (P4SR)

In the summary of the paper on the effects of air speed (Dunham *et al.* 1946) occurs the following significant sentence: 'The most reliable means of assessing the effect of any set of conditions was found to be the rate of sweating'. It is not surprising, therefore, that when the workers at the National Hospital devised a new index of stress—described in their paper 'The prediction of the physiological effects of warm and hot environments' (McArdle & Dunham, Holling, Ladell, Scott, Thomson, Weiner, 1947)—this index should have as its basis the amount of sweat produced. McArdle and his colleagues called their new scale the Predicted Four-hour Sweat Rate or, more shortly, the P4SR. In this scale the stress of the environment was defined in terms of the amount of sweat (in litres*) which would be produced by fit, acclimatized, young men when exposed to the given conditions for a period of 4 hr.

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* There are two scales of effective temperature, one for men clad in light indoor clothing and the other for men stripped to the waist; the two scales are distinct. See also p. 63.

The P4SR Nomogram

The scale, which was devised empirically, is expressed in the form of a nomogram (Fig. 4A). It was hoped, at first, that the nomogram would retain something of the simplicity of the Effective Temperature Scale nomogram, but this, by virtue of the greater number of factors to be considered, proved to be impossible. The new index of stress was concerned with hot conditions, and to this extent was more limited in its range than the Effective Temperature Scale. The actual range of air temperature covered by the new scale of stress was from 80 F to 130°F, with wet-bulb temperatures between 60°F and 100°F and air speeds of 10 to 500 ft./min. Provision was also made to allow for the effects of environments in which the mean radiant temperature of the surroundings differed from the air temperature. The level of energy expenditure (i.e., the rate of working) and the amount of clothing worn are also considered in the calculation of the index.

The nomogram was based largely on the experimental findings of Dunham *et al.* (1946) but, since these were concerned only with two levels of energy expenditure and two levels of clothing, use was also made of the findings of Benson *et al.* (1945), of a further series of sixteen experiments conducted by McArdle on men pedalling a bicycle ergometer and wearing standard army clothing, and of a very short series of experiments by Ladell and McArdle on two men working in shorts at 100 $kcal.m^{-2}.hr^{-1}$. In all these experiments the mean radiant temperature had not differed appreciably from the air temperature so, in order to provide information on the effect of alteration in the radiant heat load, 16 further experiments (p. 303) were conducted in a small cubicle which was built in one of the hot rooms at the National Hospital. It was possible to heat two of the walls and the roof of this cubicle to a temperature somewhat greater than 200°F, and thereby produce within the cubicle mean radiant temperatures approaching 130°F.

A very important feature of the nomogram as devised was that, in addition to predicting the sweat loss of men exposed for four hours to given conditions, it could also be used for estimating the increase (in degrees Fahrenheit) in the rectal temperature over four hours.

The Calculation of the P4SR Index

The nomogram (Fig. 4A) consists of three parts. The scale on the left (a single straight line) represents the globe-thermometer temperature or, when this is unknown, the dry-bulb temperature.

On the right, five straight lines constitute the wet-bulb scales (W.B.1–W.B.6). The appropriate scale to be used depends upon the air speed. Thus, if the air speed of the environment is 10 ft./min, scale W.B.6 should be used, or, if

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* As before, a litre of sweat was considered to weigh 1 kg—a convention which was followed by subsequent authors.

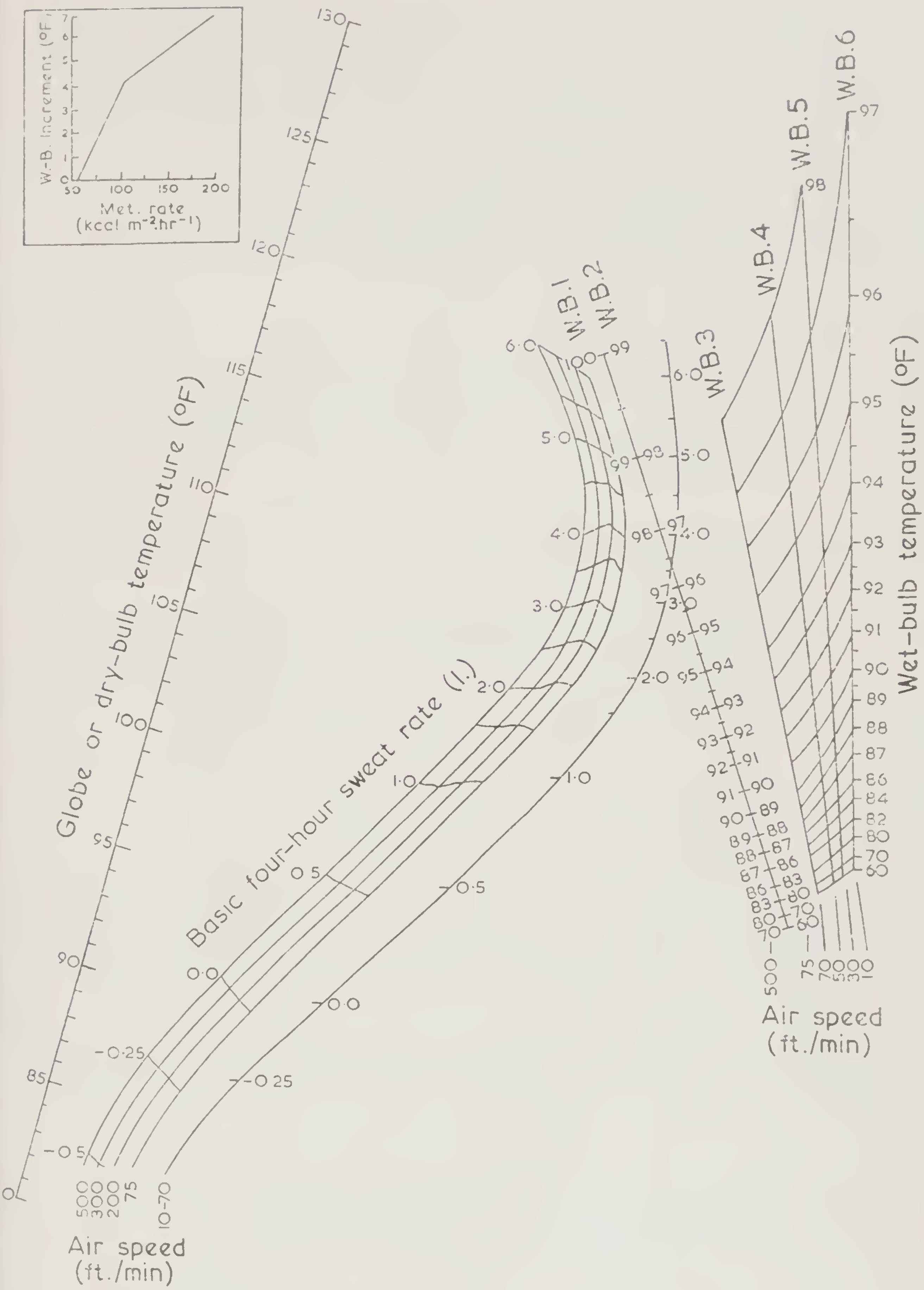

Fig. 4A. Nomogram for the calculation of the P4SR. The inset chart gives the increment to be added to the wet-bulb temperature for metabolic rates between 50 and 200 kcal.m^{-2}.hr^{-1}.

500 ft./min, scale W.B.1. For air speeds between 75 ft./min and 500 ft./min an intermediate point between the reading on W.B.1 and W.B.2 should be used.

The third part of the nomogram comprises a group of curves running downwards from right to left. These curves represent the scales for the basic four-hour sweat rate (B4SR), the appropriate curve to be used depending, as in the wet-bulb scale, upon the air speed of the environment, indicated at the lower end of the curves.

The B4SR is a stage in the calculation of the P4SR, and the two must not be confused. The B4SR by itself is without physiological significance, except that in the single case of men sitting in shorts the B4SR is equal to the P4SR. The P4SR is calculated in three stages, as follows.

Stage 1. Calculation of modified wet-bulb temperature

The wet-bulb value requires modification in the following circumstances:

(a) If the globe-thermometer temperature differs from the dry-bulb temperature the wet-bulb temperature is corrected by the addition of an amount given by the equation

$$\text{Correction} = 0{\cdot}4\ (\text{G.T.} - \text{D.B.}) \quad \ldots \quad \ldots \quad \ldots \quad (1).$$

(b) If the energy expenditure exceeds 54 $\mathrm{kcal.m^{-2}.hr^{-1}}$ (the metabolic rate of men sitting in chairs) an amount which is read off from the small inset chart is added to the wet-bulb temperature. If the metabolic rate is not known the work is classified as being either (i) sedentary, (ii) light, (iii) moderate, or (iv) heavy, and the appropriate amount to add to the wet-bulb temperature is read off from the following table.

Level of activity	*Approx. range of energy expenditure ($\mathrm{kcal.m^{-2}.hr^{-1}}$)*	*Increment in wet-bulb (°F)*
Sedentary	65	1·0
Light	100	4·0
Moderate	165	6·0
Heavy	225	7·5

(c) If the men are wearing clothing imposing a greater stress than that imposed by shorts, an appropriate amount, dependent upon the amount of clothing worn, is added to the wet-bulb temperature. In the case of men wearing overalls over shorts, the amount to be added is 1·8°F.*

Example. To calculate the modified wet-bulb temperature in the case of men working at 100 $\mathrm{kcal.m^{-2}.hr^{-1}}$ when the globe-thermometer temperature is 110°F, the dry-bulb temperature 105°F, the wet-bulb temperature 85°F and overalls are worn over shorts:

Corrections

(a) For globe-thermometer dry-bulb difference (0·4 (G.T. – D.B.)) ...	2·0
(b) For level of energy expenditure (from inset chart)	4·0
(c) For clothing (overalls over shorts)	1·8
Total correction ...	7·8

Modified wet-bulb = 85°F + 7·8°F = 92·8°F

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* The cotton drill overalls weighed approximately 1 kilogram. The amount to be added for other types of clothing can be calculated proportionately.

Stage 2. Calculation of B4SR (basic four-hour sweat rate)

A line is drawn between the point on the scale on the left representing the observed globe-thermometer temperature (or the observed dry-bulb temperature if the globe-thermometer temperature is not known) and the point representing the modified wet-bulb on the appropriate wet-bulb scale for the observed air speed. The B4SR is indicated by the point where this line intersects the appropriate curve for the given air speed on the B4SR scale.

Examples. If the air speed in the example given above had been 50 ft./min the B4SR would be 2·9 litres; if the air speed had been 300 ft./min the B4SR would be 2·4 litres.

Stage 3. Calculation of P4SR

Having obtained the B4SR, the P4SR may be easily calculated by adding to the B4SR an amount which depends on the level of energy expenditure and the amount of clothing worn, as follows.

Men sitting at rest in shorts. The B4SR and the P4SR are identical and no further calculation is required.

Men working in shorts. The P4SR is calculated from the equation

$$\text{P4SR} = \text{B4SR} + 0{\cdot}014\,(M - 54) \qquad \ldots \qquad \ldots \qquad (2),$$

where M is the metabolic rate in kcal.m^{-2}.hr^{-1}. If the energy expenditure is unknown, the appropriate value given in the table on p. 298 is assumed and substituted for M in this equation.

Men sitting in overalls worn over shorts. The P4SR is obtained by adding 0·25 to the B4SR.

Men working in overalls over shorts. The P4SR is calculated from the equation

$$\text{P4SR} = \text{B4SR} + 0{\cdot}25 + 0{\cdot}02(M - 54) \qquad \ldots \qquad \ldots \qquad (3).$$

If the energy expenditure is not known, the appropriate value given in the table on p. 298 is assumed and substituted for M in this equation.

If the clothing worn, while more than shorts, imposes a greater or lesser stress than overalls worn over shorts, the amount to be added to the B4SR should be suitably adjusted.

Example. The calculation of the P4SR in the example given previously is completed as follows. The metabolic rate was 100 kcal.m^{-2}.hr^{-1} and the clothing worn was overalls over shorts. From equation (3) the amount to be added to the B4SR is

$$0{\cdot}25 + 0{\cdot}02(100 - 54) = 1{\cdot}17 \text{ litres.}$$

The B4SR when the air movement was 50 ft./min was 2·9 litres; when 300 ft./min it was 2·4 litres. The P4SR would therefore have been 4·1 litres when the air speed was 50 ft./min and 3·6 litres when it was 300 ft./min.

'Evaporated' and 'unevaporated' sweat

The nomogram may also be used to obtain a rough indication of the amount of 'evaporated' and 'unevaporated' sweat under different conditions. The P4SR is first calculated in the manner outlined above, and then the 'evaporated' sweat is determined in the same way but using the lowest value of the wet-bulb temperature on the scale instead of the modified wet-bulb temperature. The difference between the P4SR and the 'evaporated' sweat represents the 'unevaporated' sweat.

Example. In the case of men sitting in overalls worn over shorts at dry-bulb 120°F, wet-bulb 85°F, and air speed 50 ft./min, by joining 120°F on the dry-bulb scale to the modified wet-bulb temperature of 86·8°F (85° + 1·8°) on the scale W.B.4, the B4SR is given as 2·6. The P4SR is therefore 2·6 + 0·25 = 2·85 litres. By joining 120°F on the dry-bulb scale to 60°F on scale W.B.4, the B4SR is given as 2·15 and the P4SR or 'evaporated' sweat is therefore 2·4 litres. The 'unevaporated' sweat would therefore be approximately 2·85 — 2·4 = 0·45 litres.

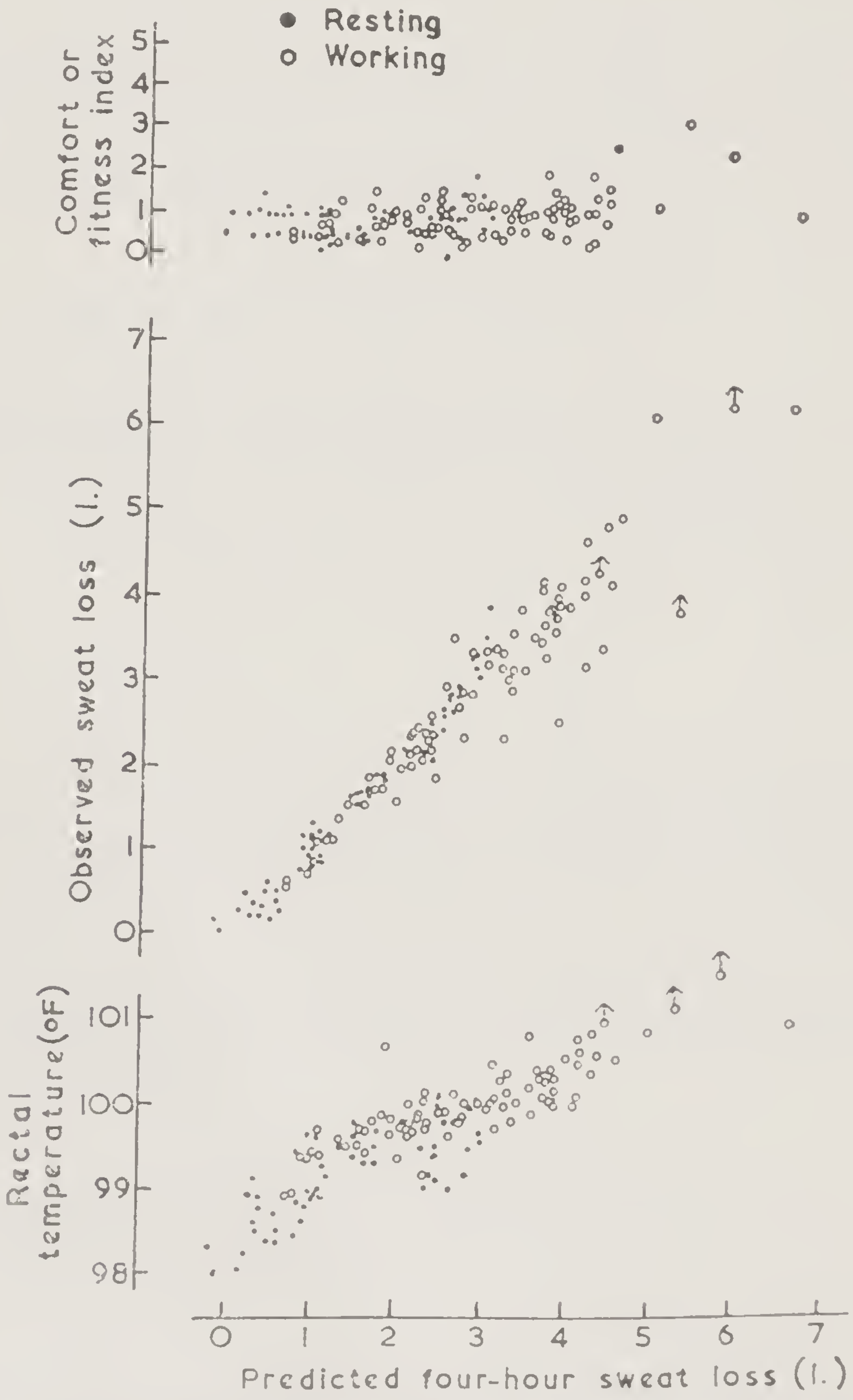

FIG. 5A. The relation between predicted four-hour sweat loss and mean final rectal temperature, observed sweat loss and Comfort or Fitness Index of men in shorts. The sign ↑ indicates that one or more of the men failed to complete the experiment.

THE PREDICTION OF RECTAL TEMPERATURE

The increase in rectal temperature in degrees Fahrenheit at the end of a four-hour period in a warm or hot environment may be predicted in fully acclimatized individuals by multiplying the P4SR by 0·4. An approximate estimate of the actual rectal temperature may be made by adding this increase to the arbitrary figure of 98·7°F.

COMPARISON OF OBSERVED AND PREDICTED SWEAT LOSSES

To test the accuracy with which the P4SR Index predicts the amount of sweat lost, the observed mean sweat losses in the experiments of Dunham *et al.* (1946) were plotted against the values predicted by the P4SR nomogram (Fig. 5A and

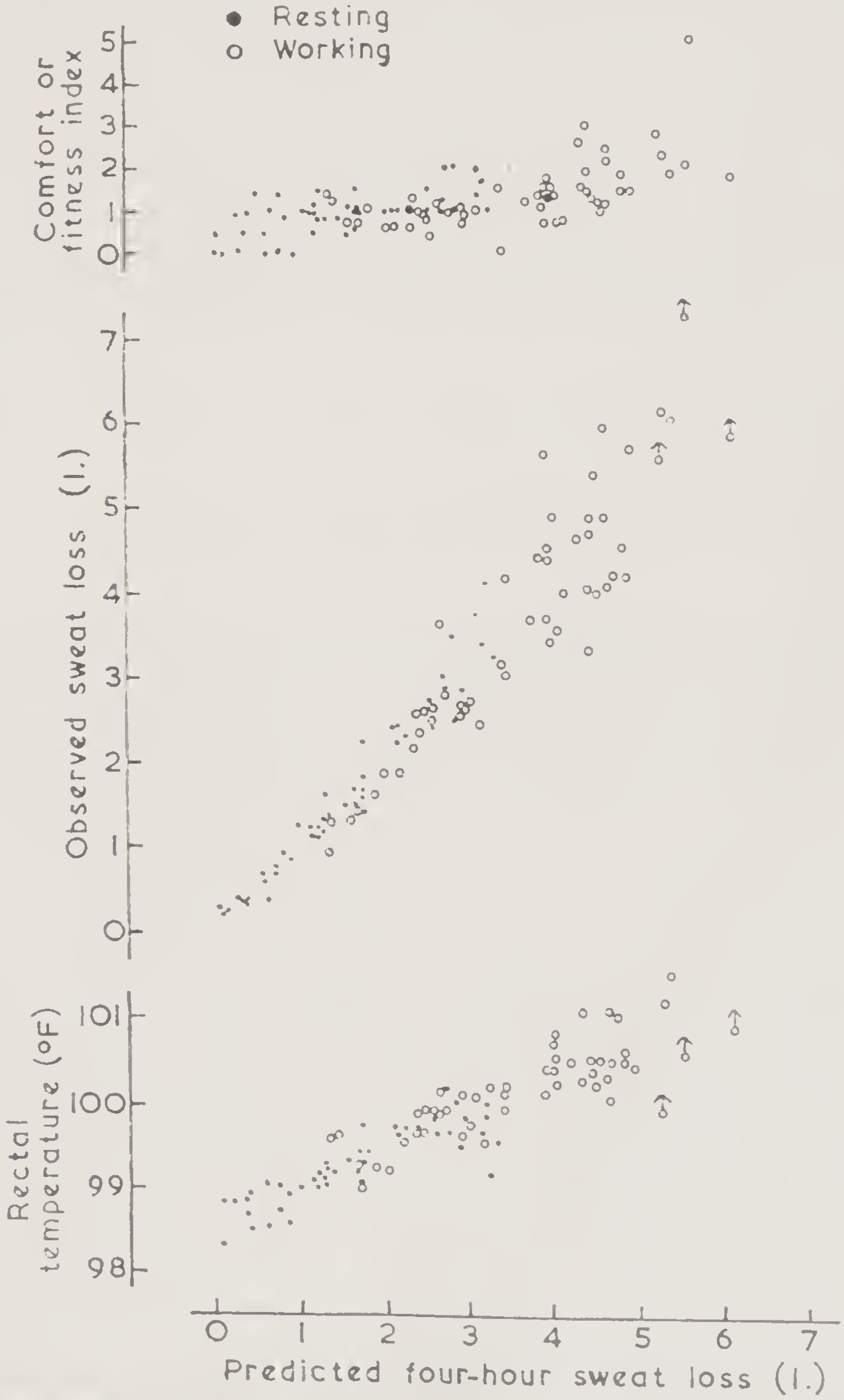

FIG. 6A. The relation between predicted four-hour sweat loss and mean final rectal temperature, observed sweat loss and Comfort or Fitness Index of men in overalls. The sign ↑ indicates that one or more of the men failed to complete the experiment.

6A). It is clear that the two sets of values are in very good agreement. Table 15A shows that the correlation between the observed and predicted values is extremely good, but it must be remembered that the observed values are not those for individuals but for the average rates of sweating observed in experiments in which several subjects commonly took part.

Reactions to hot environments differ widely from person to person. Large variations occur in the amount of sweat secreted under the same conditions by different persons, so that it is impossible for the P4SR to predict the sweat loss of any one individual; it is clear that it can predict only the average for a large group of individuals. McArdle *et al.* (1947) pointed out that for some environmental combinations results were available only for one subject, and that in these conditions the predicted sweat loss might differ widely from the observed sweat loss, and it was suggested that this accounts for most of the variation between the predicted and observed values. The variation between individuals was most apparent in conditions in which the amount of unevaporated sweat was large, i.e., at high wet-bulb temperatures. Differences between individuals of as much as 2·5 or even 3 litres in 4 hr were noted. In hot dry conditions, when there was little unevaporated sweat, there was little variation between individuals.

When the observed mean sweat losses in all the experiments conducted at the National Hospital other than those of Dunham *et al.* (1946) were plotted against the predicted values, the scatter was found to be somewhat greater than that shown in Fig. 5A and 6A.

THE P4SR AND OTHER MEASURES OF STRESS

Rectal Temperature

The relation between the P4SR and the mean final rectal temperature in the experiments of Dunham *et al.* (1946) is also illustrated in Fig. 5A and 6A. It will be seen that the final rectal temperature correlated well with the P4SR, both for working and resting men whether they were clad in overalls or in shorts. This is further illustrated in Table 16A, but again it must be stressed that the correlation coefficient applies to the mean value for all subjects in each experiment and not to the values for individual subjects. The values given in Fig. 5A and 6A are also mean values and there was, as in the case of sweat loss, considerable variation between individuals. It was considered that this was largely due to the wide variation in the initial rectal temperature of the subjects. The mean rectal temperature at the beginning of the experiments was 98·93°F, but the range was from 97·6° to 100·1°F (S.D. 0·366°F). In addition to this source of variation there was, of course, the expected individual variation in the response to the same treatment. When the mean final rectal temperatures in all the experiments on which the P4SR was based, other than those of Dunham *et al.* (1946), was plotted against the corresponding P4SR value, the scatter was much greater.

The use of the nomogram to predict the final rectal temperature was not discussed specifically in the original paper. However, the relation between the final rectal temperature and the P4SR values plotted in Fig. 5A and 6A show that the number of degrees by which the rectal temperature would exceed 98·7°F was approximately four-tenths of the numerical value of the corresponding P4SR Index.

Comfort and Fitness Indices

In Fig. 5A and 6A is also shown the relation between the P4SR and, for the working subjects, the Fitness Index, and for the sitting subjects, the Comfort Index. This last was derived from the Comfort Rating of Dunham *et al.* (1946) by modifying the values so that 5 became 0, 4 became 1, and so on, so that it corresponded to the Fitness Index. Inspection will serve to show that there was little correlation between these indices and the P4SR. This was considered to be due to the unsatisfactory nature of these ratings rather than to any failure by the P4SR to assess environmental stress. The authors of the paper stated 'It has been found difficult to secure an accurate appraisal of the comfort or rather the degree of discomfort of the various conditions tested. Comfort votes have undoubtedly been occasionally influenced by factors other than the conditions under test, and too much importance should not be attached to the results.'

THE P4SR INDEX AND THE EFFECTIVE TEMPERATURE SCALE

The P4SR Index was compared with the findings of Gagge *et al.* (1937) and with the Index of Physiological Effect of Robinson *et al.* (1945), but, because of the importance attached to it by the Habitability Subcommittee (Chapter 1), the most important comparison was that made with the Effective Temperature Scale.

In Fig. 7A is shown the result of plotting the mean sweat loss, final rectal temperature and Comfort or Fitness Index, in all those experiments of Dunham *et al.* (1946) in which five or more men took part, against the corresponding P4SR Index. In Fig. 8A the same results are plotted against the Effective Temperature Scale using the 'normal' scale for men wearing overalls and the 'basic' scale for men wearing shorts.

It was concluded from the comparison of Fig. 7A and Fig. 8A that 'It is readily apparent that the P4SR is distinctly superior to the E.T. Scale with regard to the closeness of fit of sweat rate, final rectal temperature and comfort or fitness index, even allowing for the curved pattern of response to increasing effective temperature, the different response to the two levels of metabolism and the two types of clothing.'

INCREASED MEAN RADIANT TEMPERATURE AND THE P4SR

Bedford (1946) had suggested that the Effective Temperature Scale could be modified to embrace the effect of the mean radiant temperature of the surroundings by substituting the globe-thermometer reading for the dry-bulb temperature when calculating the effective temperature. McArdle and his co-workers thought that 'Bedford's modification of the Effective Temperature Scale to include the effects of radiation is based on theoretical considerations and awaits experimental proof.' A short series of experiments was therefore performed (in the cubicle described on p. 296) to test the hypothesis underlying Bedford's modification of the Effective Temperature Scale.

The series consisted of eight pairs of experiments. In the first member of each pair of experiments the mean temperature of the surroundings was greater than that of the surrounding air. In the second member of each pair the surroundings and the air were at the same temperature, which was adjusted to be substantially the same as the globe-thermometer temperature in the first experiment. In all other respects the two experiments were similar.

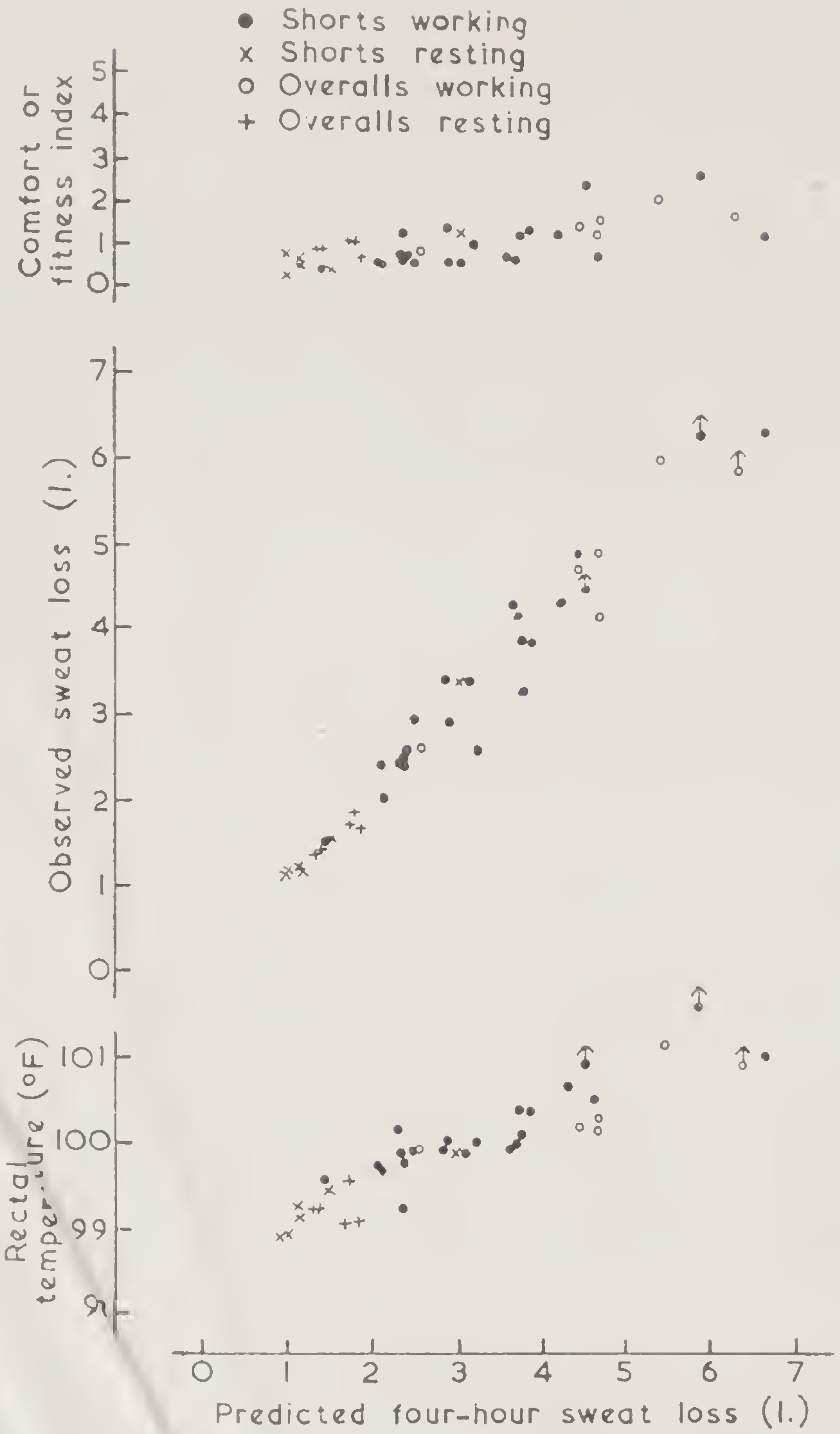

FIG. 7A. The relation between predicted four-hour sweat loss and mean final rectal temperature, observed sweat loss and Comfort or Fitness Index. The results from experiments on five or more men only are given. The sign ↑ indicates that one or more of the men failed to complete the experiment.

The results of these experiments are set out in Table 17A. It will be observed that there is one constant difference between the two types of experiment. In those experiments in which the globe-thermometer reading was above air temperature the amount of unevaporated sweat was always greater than in those in which there was no disparity between the air temperature and the mean radiant temperature.

The authors considered that when the amount of radiation was small, or the wet-bulb temperature comparatively low, or the men were sitting in shorts, there was little difference between the two types of environment. When, however, the men wore overalls, or the wet-bulb temperature was high, or the air speed

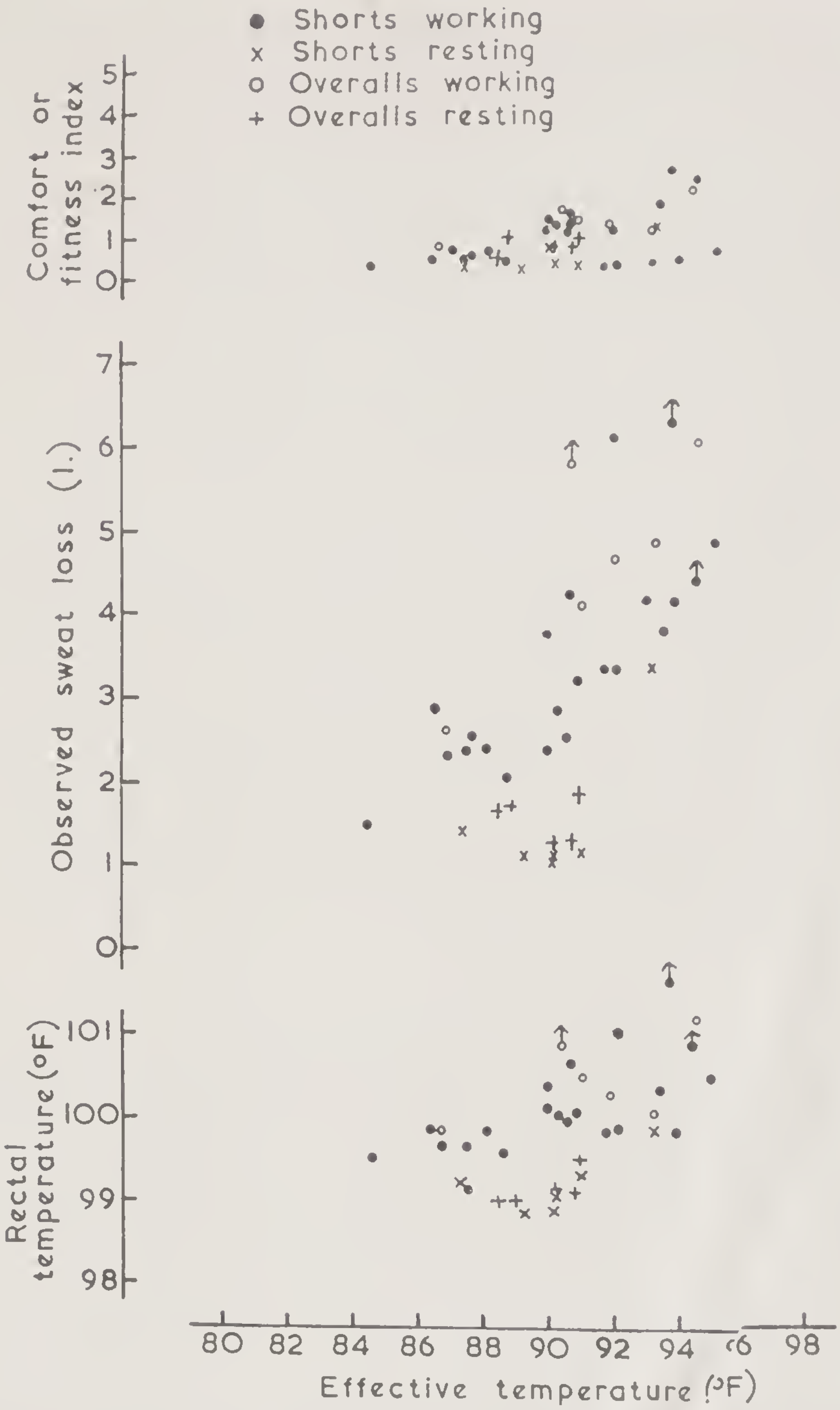

FIG. 8A. The relation between effective temperature and mean final rectal temperature, observed sweat loss and Comfort or Fitness index. The results from experiments on five or more men only are given. The sign ↑ indicates that one or more of the men failed to complete the experiment

low, the globe-thermometer reading appeared to under-estimate the stress imposed by the increased radiation. They concluded therefore, that 'these experiments do not fully support Bedford's hypothesis'.

It was found that if the globe-thermometer reading was used instead of the dry-bulb temperature in calculating the P4SR, the agreement between the observed and predicted values would have been poor in Experiments 9 and 13. But it was found empirically that a satisfactory agreement could be achieved if, in addition to using the globe-thermometer reading, the wet-bulb temperature was 'modified' by adding to the wet-bulb temperature 0·4 times the difference between the globe-thermometer reading and the dry-bulb temperature. This method has been used in calculating the P4SR values for the eight pairs of experiments set out in Table 17A.

LIMITING ENVIRONMENTS AND THE P4SR

Examination of Fig. 5A and 6A will show that a predicted four-hour sweat loss of 4·5 litres was the lowest value at which one or more of the subjects was unable to complete an experiment. This value was therefore taken provisionally as representing a limiting value for fit, young acclimatized men, above which conditions would become intolerable to an increasing number of men.

It was thought that although there was not sufficient evidence to show conclusively that in all conditions a P4SR of 4·5 litres is the limiting value, there was good reason to believe that some such single figure might be used in defining these limits.

It was clear that the choice of a definite value for the upper limit of tolerable conditions presented great difficulties. It would naturally vary greatly with the degree of acclimatization of the men concerned and the type of occupation in which they were engaged. In laying down any definite value for an 'upper tolerable limit' it becomes necessary to allow a very considerable margin of safety. The authors summed up the position very adequately in the concluding paragraph of the summary of their paper, in which they stated 'A P4SR of 4·5 litres is tentatively suggested as the upper limit for fit acclimatized young men above which an increasing number will find the conditions beyond their endurance. Efficiency for even the simplest tasks will have been affected before this value is reached.'

THE VALIDITY OF THE P4SR

Inherent in the use of the P4SR Index as a measure of environmental stress is the assumption that the amount of sweat produced in a given environment is a measure of the physiological strain produced in the organism by that environment. The validity of this assumption has been discussed at length in Chapter 10, but it is important to observe here that McArdle and his co-authors were fully aware of the difficulty. They state 'It is not claimed that the P4SR predicts with invariable accuracy the sweat rate even of a group large enough for individual differences to be submerged. Above a P4SR of 5·0 litres the actual values for sweat rates have tended to fall below the predicted values, although the actual rectal temperatures continued to be in fairly good agreement with those predicted. It is presumed that the cause of this discrepancy was that there was a limit to the rate at which the men were able to sweat, and that in acclimatized subjects this became manifest about a rate of 5 litres of sweat in 4 hr. It is likely that in such circumstances the P4SR continued to indicate the stress of the conditions with tolerable accuracy, but the actual sweat rate was no longer a guide to their severity. It should be mentioned that for a number of individuals such conditions would be either at, or beyond, the limits of their endurance. Below a 4-hr sweat rate of about 5 litres the correlation between sweat rate and rectal temperature has been reasonably close, but there has been a tendency in hot dry conditions for the sweat rate to be disproportionately greater than the rectal temperature. This has to some extent been allowed for in the P4SR which therefore tends in these circumstances to under-estimate slightly the sweat rate, and over-estimate slightly the rise in rectal temperature, whilst probably indicating the overall severity of the conditions tolerably well.'

This statement considerably complicates the original simple concept. The actual sweat loss is replaced by a conventionalized sweat loss, which takes into consideration not only sweat loss but other indications of physiological strain, in particular the rectal temperature.

This new concept has far-reaching implications. For example, it extends the upper end of the range of P4SR values. Furthermore, it justifies the provision in the nomogram of negative values for the P4SR (which, in terms of the original definition, are clearly unacceptable) and thereby extends the lower end of the range as well.

Summary

An account has been given of the work done at the National Hospital, Queen Square, London, as reported in three papers (Benson *et al.*, 1945; Dunham *et al.*, 1946; McArdle *et al.*, 1947).

In the first paper, 'The ability to work in severe heat' (Benson *et al.*, 1945), it was concluded that for fit, young men, artificially acclimatized to working in the heat:

1. Increasing the wet-bulb temperature in very hot conditions greatly increased the stress of the environment, whereas increasing the dry-bulb temperature had comparatively little effect.
2. Increasing the air speed from 10 to 200 ft./min in hot humid conditions raised the wet-bulb temperature at which work was possible by 2 to 3°F, but increasing the air speed from 50 to 300 ft./min in hot dry conditions had comparatively little effect.
3. The wearing of heavy protective clothing instead of shorts reduced by some 3°F the limiting wet-bulb temperature at which work was possible.
4. In very hot conditions the Effective Temperature Scales over-emphazise the part played by the dry-bulb temperature in comparison with that of the wet-bulb temperature in contributing to the stress of the environment, and under-estimates the deleterious effect of very low air speeds (e.g., 10 ft./min) in hot humid conditions.

In the second paper, 'The effects of air movement in severe heat' (Dunham *et al.* 1946), it was concluded that under the conditions of the experiments:

1. The rate of sweating was the most reliable means of assessing the thermal stress of a hot environment.
2. The deleterious effects of low air speeds (10 to 75 ft./min) were most marked for men working in overalls in hot humid conditions and only slight for men wearing shorts and resting in a hot dry environment.
3. Increasing the air speed above 75 ft./min at first always produced some improvement in conditions, but above 300 ft./min there was little further improvement. Indeed, when the air temperature was above 100°F increasing the air speed above 300 ft./min increased the stress of the environment.
4. The Effective Temperature Scale does not indicate accurately the level of stress imposed by low air speeds in hot humid conditions and at air temperatures above body temperature it indicates (provided the wet-bulb temperature is not above 96°F) a continuous improvement with rising air speeds instead of an improvement followed by deterioration.

In the third paper, 'The prediction of the physiological effects of warm and hot environments', McArdle *et al.* (1947) presented a nomogram by means of which it is possible to assess, in terms of the amount of sweat which would be lost, the physiological effect of a given hot environment. The details are as follows.

1. The Index used to assess the physiological effect of the environment is called the Predicted Four-hour Sweat Rate (P4SR) and corresponds to the amount of sweat, in litres, which would be secreted by fit, acclimatized, young men in the conditions in question.

2. The range of conditions covered is: dry-bulb or globe-thermometer temperatures from 80°F to 130°F; wet-bulb temperatures from 60°F to 100°F; air speeds from 10 ft./min to 500 ft./min; rates of energy expenditure from 54 kcal.m^{-2}.hr^{-1} to 200 kcal.m^{-2}.hr^{-1}; and a range of clothing.

3. The P4SR was found to agree closely with the mean sweat loss observed in over 1,000 individual four-hour experiments over the range of conditions covered by the nomogram. The P4SR can therefore be used for estimating the salt and water requirements in given hot conditions, but allowance should be made for the variations which occur in the rate of sweating of different individuals.

4. The P4SR correlated well with the experimentally observed mean final rectal temperature. The increase in rectal temperature in these experiments was observed to be 0·4 times the P4SR. An approximate estimate of the final rectal temperature can be obtained by adding the amount of this change to 98·7°F.

5. It was considered that experimentally determined mean sweat losses and mean final rectal temperatures correlated considerably better with the P4SR Index than with the effective temperature of the environment, even when allowance was made for the fact that the response to any given effective temperature varies with the rate of energy expenditure and the amount of clothing worn.

6. A P4SR Index of 4·5 was tentatively suggested as the limit of tolerance for fit, acclimatized young men above which an increasing number would find conditions beyond their endurance; it was recognized, however, that—even in the simplest tasks—efficiency would be affected before this value was reached.

TABLE 1A

Experiments of Benson et al. The effects on men wearing anti-flash clothing at a constant air speed (75 ft./min) of three environments having the same effective temperature but different levels of wet-bulb temperature

Expt. No.	No. of subjects	Environment				Mean rectal temperature (°F)			Mean sweat loss (g)	Fitness Index		
		Dry-bulb (°F)	Wet-bulb (°F)	Rel. hum. (%)	Effect. temp. (°F)	End of 1st work	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
5	8	92·9	91·05	93·0	91·2	102·05	99·95	102·15	4193	5	3	2·4
6	8	110·2	85·05	36	91·1	101·2	99·2	100·9	3889	8	—	1·1
7	8	114·5	83·55	28	91·1	100·9	99·4	101·1	3907	8	—	1·0

TABLE 2A

Experiments of Benson et al. Comparison of the effects of hot dry and hot wet environments at a constant air speed (approx. 75 ft./min) on men wearing anti-flash clothing and shorts

Expt. No.	No. of subjects	Environment			Clothing	Mean rectal temperature (°F)		Mean sweat loss (g)	Mean Fitness Index
		Dry-bulb (°F)	Wet-bulb (°F)	Effect. temp. (°F)		Final resting	Final work		
10	4	121·0	84·4	92·8	anti-flash	99·5	101·3	4291	1·2
3	4	91·5	90·1	90·0	anti-flash	99·35	101·55	5192	1·4
11	8	119·8	89·15	95·0	anti-flash	99·9	101·7	5463	2·1
9	8	94·7	92·8	92·8	anti-flash	100·3(1)	103·7(7)	5505(1)	3·6
30	10	119·8	89·1	95·0	anti-flash	99·8	101·4	5485	1·2
26	8	95·35	92·65	92·8	anti-flash	99·9	101·45(1)	4758	3·2
36	8	120·25	88·9	94·5	shorts	99·65	101·05	4568	1·0
34	12	95·0	93·15	92·8	shorts	99·7	101·6	3228	1·7
37	10	120·4	91·0	96·0	shorts	99·9	101·25	4886	1·2
35	11	96·1	93·9	93·5	shorts	100·1	101·8(1)	4611(1)	1·8

The numbers in brackets indicate the numbers of subjects who either had to retire from an experiment or were unable to complete a period of work and hence are not included in the mean values

TABLE 3A

Experiments of Benson et al. A comparison of the effects on men wearing shorts and anti-flash clothing of hot wet (Expt 39 and 41) and hot dry (Expt 40 and 42) environments having the same effective temperature (air speed approx. 75 ft./min)

Expt. No	No. of subjects	Clothing	Environment				Mean rectal temperature (°F)			Mean sweat loss (g)		Fitness Index		
			Dry-bulb (°F)	Wet-bulb (°F)	Rel. hum. (%)	Effect. temp. (°F)	Initial	Final resting	Final working	Resting	Working	No. less than 3	No. 3 or over	Mean grading
39	11	Shorts	96·1	94·05	93	shorts	98·9	99·45	101·15	2121	666	11	—	1·0
40	11	Shorts	119·7	87·4	28	shorts	98·8	99·5	100·8	2455	999	11	—	1·0
41	15	Anti-flash	95·3	93·1	93	anti-flash	98·95	99·75	101·7	2769	1052	11	4	2·25
42	20	Anti-flash	120·3	85·6	25	anti-flash	99·15	99·7	101·1	2609	1067	20	—	1·0

TABLE 4A

Experiments of Benson et al. The effect of variations in air speed on men wearing anti-flash clothing in hot wet environments

Expt. No.	No. of subjects	Environment				Mean rectal temperature (°F)				Mean sweat loss (g)	Fitness Index		
		Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	End of 1st work	At 90 min	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
12	17	91·8	89·85	10	90·2	101·15	100·85	99·95	101·8*	5262	13	4	2·0
13	16	92·0	90·15	50	90·2	101·0	100·5	99·35	101·2	4030	16	—	1·7
4	8	92·2	90·0	75	90·0	101·35	100·1	99·4	101·25	4371	8	—	1·2
14	8	92·45	90·05	125	89·7	101·35	100·0	99·3	101·05	3421	8	—	1·1
15	8	91·7	90·1	200	88·9	101·0	99·75	98·9	100·85	3828	8	—	1·0

* Two subjects were unable to finish the second working period and are not included in this mean.

TABLE 5A

Experiments of Benson et al. The effect of variations in air speed on men wearing shorts in hot wet environments

Expt. No.	No. of subjects	Environment				Mean rectal temperature (°F)				Mean sweat loss (g)	Fitness Index		
		Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	End of 1st work	At 90 min	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
45	10	91·8	90·4	10	90·3	100·7	99·9	99·45	100·75	3083	10	—	1·0
32	10	91·85	90·2	75	89·5	100·45	99·45	99·1	100·3	1808	10	—	1·1
46	10	92·2	89·95	200	88·0	100·4	99·2	98·95	100·25	1782	10	—	1·0

TABLE 6A

Experiments of Benson et al. The effect of variations in air speed on men wearing anti-flash clothing in hot dry environments

Expt. No.	No. of subjects	Environment				Mean rectal temperature (°F)				Mean sweat loss (g)	Fitness Index		
		Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	End of 1st work	At 90 min	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
49	9	119·7	87·25	50	94·0	101·35	100·5	99·7	101·15	4445	8	1	1·7
50	9	121·7	87·0	125	94·0	101·0	100·2	99·6	100·95	4262	9	—	1·55
51	9	119·8	86·95	200	93·2	100·95	99·85	99·45	101·0	4212	9	—	1·6

TABLE 7A

Experiments of Benson et al. The effect of variations in air speed on men wearing shorts in hot dry environments

Expt. No.	No. of subjects	Environment				Mean rectal temperature (°F)				Mean sweat loss (g)	Fitness Index		
		Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	End of 1st work	At 90 min	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
36	9	120·25	88·9	75	94·5	100·95	99·9	99·65	101·05	4568	9	—	1·0
52	9	120·4	88·95	200	94·2	101·05	99·9	99·7	101·05	4617	9	—	1·1
37	10	120·4	91·0	75	96·0	101·2	100·25	99·9	101·25	4886	10	—	1·25
53	10	120·5	91·0	200	95·8	101·05	100·0	99·85	101·25	4510	10	—	1·2

TABLE 8A

Experiments of Benson et al. The effects of loading 108 lb. cordite charges and of step-climbing in hot humid conditions on men wearing anti-flash clothing and shorts. The experiments had two 20 min periods of work, except Expt. 64 which had two 30 min periods

Expt. No.	No. of subjects	Clothing	Type of work	Environment				Mean rectal temperature (°F)			Mean sweat loss (g)	Fitness Index		
				Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	End of 1st work	Final resting	End of 2nd work		No. less than 3	No. 3 or over	Mean grading
54	12	anti-flash	step-climbing	94·2	92·0	75	92·0	100·35	99·6	100·8	4100	12	—	1·25
55	12	anti-flash	loading	94·2	92·25	75	92·2	100·3	99·7	101·1	4148	10	2	2·0
56	12	shorts	step-climbing	96·0	94·15	75	93·8	100·25	99·75	100·7	3741	12	—	1·4
57	12	shorts	loading	96·05	93·95	75	93·5	100·2	99·55	100·8	3507	11	1	1·75
58	12	anti-flash	loading	90·0	87·15	75	87·6	100·7	99·35	100·5	2206	12	—	1·0
59	7	anti-flash	loading	95·0	93·0	75	93·0	100·9	99·8	101·35	4903	7	—	1·3
60	8	shorts	loading	96·65	95·0	75	95·7	100·7	100·35	101·8	5746	6	2	2·1
61	10	anti-flash	step-climbing	92·75	91·5	10	92·0	100·25	100·0	101·0	4804	7	3	2·2
62	6	anti-flash	step-climbing	94·1	92·4	10	93·0	99·7	100·85	100·6*	5785	3	3	2·75
63	6	anti-flash	step-climbing	95·25	92·95	200	92·0	100·5	99·2	100·3	3491	6	—	1·15
64	5	anti-flash	step-climbing	93·5	93·0	200	91·7	101·3	99·6	101·35	4427	4	1	2·2

*The subjects were unable to complete the last work period in these conditions.

TABLE 9A

Experiments of Benson et al. Limiting environments for men in anti-flash clothing and in shorts, when step-climbing and when loading dummy cordite charges

Type and duration of work	Clothing	Air speed (ft./min)	Limiting wet-bulb temperature (°F)	
			Humid environmentst (Rel. hum. 100%)	Hot dry environments (Dry-bulb 120°F)
Two 30 min periods of step-climbing in four hours	Anti-flash	10	88·5	—
	Anti-flash	50	90·0	88·0
	Anti-flash	75	91·0	88·5
	Anti-flash	200	92·0	89·0
	Shorts	10	92·0	—
	Shorts	75	93·5	92·0
	Shorts	200	94·0	92·0
Two 20 min periods of step-climbing in four hours	Anti-flash	10	90·5	—
	Anti-flash	75	92·5	—
	Anti-flash	200	93·5	—
	Shorts	75	95·0	—
Two 20 min periods of loading in four hours	Anti-flash	75	92·0	—
	Shorts	75	94·0	—

TABLE 10A

Experiments of Dunham et al. The effects of different air speeds at dry-bulb temperatures 90°, 100° and 120° F, and wet-bulb temperatures 83° and 88° F on men performing the 'Queen Square Routine' and wearing naval overalls over shorts

Subject	Environment				Sweat loss (g)		Rectal temperature (°F)			Pulse (beats/min)		Fitness Index
	Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	Total (4-hr)	In clothes	Initial	End of Work III	Final	End of Work III	Final	
Ba.M.	92·3	83·1	10	86·3	2601	1242	98·9	100·0	99·9	130	130	1·3
Ba.M.	89·8	83·0	100	84·5	1687	433	98·8	99·4	99·3	100	104	1·0
Ba.M.	90·1	83·0	260	83·3	1446	238	99·0	99·6	99·0	99	104	0·8
Ba.M.	90·0	83·0	395	82·1	1385	214	99·0	99·5	99·3	100	108	0·8
Bg.Je.	92·4	87·9	10	89·0	3353	1916	98·6	100·7	100·5	140	138	1·9
Bg.Je.	90·0	88·1	100	87·9	2505	1548	98·7	100·2	99·9	129	126	1·0
Bg.Je.	90·2	88·0	275	86·3	1925	886	98·6	99·7	99·5	104	106	0·8
Bg.Je.	90·2	88·0	460	85·1	1854	875	98·7	99·6	99·2	98	97	0·8
Ba.M.	100·1	83·1	20	88·4	2527	945	98·7	99·9	99·6	120	120	1·0
Ba.M.	99·9	83·1	100	87·8	2387	595	98·7	99·8	99·6	104	110	0·8
Ba.	100·0	83·3	260	86·9	2662	415	99·0	99·9	99·9	108	112	1·0
Ba.M.	99·9	83·1	395	86·1	2451	251	98·8	99·6	99·6	106	109	1·0
Bg.Je.	100·0	88·0	20	91·2	4260	2015	98·7	101·1	101·0	148	155	2·1
Bg.Je.	100·1	88·1	100	90·9	3213	1402	98·9	100·0	100·1	125	132	1·5
Bg.Je.	100·1	88·1	275	89·8	2474	586	99·0	99·8	99·5	120	124	1·0
Bg.Je.	100·2	88·2	460	88·8	2716	716	99·0	100·0	100·1	129	122	0·9
Ba.M.	120·0	83·1	50	92·1	4093	1001	98·8	100·6	100·2	121	139	1·5
Ba.M.	120·4	83·1	100	92·0	3481	639	98·8	100·6	100·8	130	138	1·3
Ba.M.	120·3	83·1	260	91·4	3543	210	98·9	100·0	100·2	120	132	1·3
Ba.M.	119·5	83·0	395	90·7	4006	334	99·4	100·0	100·4	124	141	0·8
Bg.Je.	120·0	88·0	50	94·5	—*	—*	98·8	102·3	—*	174	—*	5·0
Bg.Je.	119·8	87·4	100	94·0	4957	1526	99·1	101·8	101·5	156	158	3·0
Bg.Je.	120·0	87·9	275	93·7	3988	710	99·0	100·6	100·5	146	146	1·0
Bg.Je.	119·8	88·1	460	93·1	4155	525	98·8	100·6	100·6	140	136	1·9

* Both subjects were unable to complete the experiment

TABLE 11A

Experiments of Dunham et al. The effects of different air speeds at dry-bulb temperatures 90°, 100° and 120°F, and wet-bulb temperatures 83° and 88°F on men performing the 'Queen Square Routine' and wearing shorts

Subject	Environment				Sweat loss (g)		Rectal temperature (°F)			Pulse (beats/min)		Fitness Index
	Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	Total (4-hr)	In clothes	Initial	End of Work III	Final	End of Work III	Final	
U.C.	92·3	83·1	10	86·0	1548	301	98·9	99·7	99·7	113	118	1·1
U.C.	89·8	83·0	100	83·1	1125	79	99·2	99·8	99·7	105	112	1·0
U.C.	90·1	83·0	335	80·4	1040	45	99·2	99·6	99·4	100	108	0·8
U.C.	90·0	83·0	520	78·5	693	21	99·2	99·5	99·4	112	114	0·5
Ja.R.	92·4	87·9	10	88·8	2879	614	98·9	100·0	100·1	118	116	1·5
Ja.R.	90·0	88·1	100	87·0	1661	448	99·0	100·0	99·7	110	108	1·5
Ja.	90·2	88·0	335	84·5	1276	121	98·6	99·9	99·6	94	96	1·3
Ja.R.	90·2	88·0	660	81·5	1043	106	99·0	99·7	99·4	90	96	1·0
U.C.	100·1	83·1	20	87·7	1906	204	98·8	99·9	99·8	108	117	1·0
U.C.	99·9	83·1	100	86·3	1708	131	99·0	99·7	99·8	95	106	0·8
C.	100·0	83·3	335	85·0	2121	25	100·1	100·9	100·7	132	136	1·0
U.C.	99·9	83·1	520	84·0	2016	49	99·3	99·9	99·9	111	110	0·8
Ja.R.	100·0	88·0	20	91·0	3356	750	98·8	100·4	100·1	114	122	1·1
Ja.R.	100·0	88·1	100	89·8	2328	432	99·0	100·1	99·9	108	115	1·4
Ja.R.	100·1	88·1	333	88·7	2005	120	99·2	99·8	99·7	100	112	0·8
Ja.R.	100·2	88·2	660	87·3	2219	71	99·1	100·1	100·0	110	106	1·3
U.C.	120·0	83·1	50	91·5	2904	186	99·0	100·6	100·5	118	136	1·0
U.C.	120·4	83·1	100	91·1	3097	159	99·2	100·3	100·3	125	136	1·3
U.C.	120·3	83·1	335	90·6	3473	35	99·3	100·4	100·8	126	140	1·1
U.C.	119·5	83·0	520	90·0	3690	46	98·9	100·1	100·4	116	130	1·0
Ja.R.	120·0	88·0	50	94·1	4934	641	98·6	100·6	100·6	127	144	1·5
Ja.R.	119·8	87·3	100	93·5	3958	482	98·9	100·5	100·2	118	124	2·1
Ja.R.	120·0	87·9	330	93·2	4218	172	99·2	100·4	100·3	124	124	1·1
Ja.R.	119·8	88·0	660	92·8	4718	179	99·2	100·5	100·5	126	123	1·1

TABLE 12A

Experiments of Dunham et al. The effects of different air speeds at dry-bulb temperatures 90°, 100° and 120°F and wet-bulb temperatures 83° and 88°F on men sitting throughout the four-hour experiments and wearing overalls

Subject	Environment				Sweat loss (g)		Rectal temperature (°F)			Pulse (beats/min)		Comfort Rating
	Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	Total (4-hr)	In clothes	Initial	Average for last 3 hr	Final	Average for last 3 hr	Final	
Ja.R.	92·3	83·1	10	86·3	927	310	99·0	98·5	98·9	90	86	3·5
Ja.R.	89·8	83·1	100	84·7	715	85	98·9	99·0	99·0	90	92	3·5
Ja.R.	90·0	83·0	330	82·3	401	19	98·7	98·6	98·5	93	92	4·0
Ja.R.	90·0	83·0	800	80·2	419	43	99·1	98·8	98·8	90	83	4·0
Ba.M.	92·4	87·9	10	89·0	1604	1000	98·5	99·0	99·3	103	104	3·5
Ba.M.	90·2	88·0	100	87·9	645	230	98·5	98·6	98·7	87	90	4·0
Ba.M.	90·2	88·0	295	86·1	340	—	98·9	98·5	98·5	98	96	4·5
Ba.M.	90·2	87·9	600	83·5	365	115	99·1	98·9	98·9	82	84	4·5
Ja.R.	100·1	83·1	20	88·4	1115	149	98·8	99·1	99·2	88	82	4·0
Ja.R.	99·5	83·1	100	87·8	1227	105	99·0	99·2	99·1	89	87	4·0
Ja.R.	100·1	83·1	330	86·5	1128	17	99·0	99·1	99·0	95	90	4·0
Ja.R.	100·0	83·0	800	84·3	1206	4	98·8	99·0	99·0	90	88	4·0
Ba.M.	100·0	88·0	20	91·1	2289	1242	98·7	99·4	99·7	107	112	4·0
Ba.	100·1	88·0	100	90·6	1636	550	99·0	99·0	99·1	100	96	4·0
Ba.M.	100·1	88·1	295	89·8	1115	120	99·1	99·0	99·0	96	96	4·5
Ba.M.	100·4	88·2	600	88·2	1350	123	99·0	99·0	98·9	98	92	4·5
Ja.R.	120·0	83·1	50	92·0	2763	625	98·7	99·6	99·8	93	96	3·5
Ja.R.	120·0	82·8	100	91·7	2395	219	98·9	99·5	99·6	106	90	4·0
Ja.R.	120·3	83·1	330	91·0	2508	57	99·0	99·6	99·5	99	103	3·0
Ja.R.	119·7	83·1	800	90·0	3862	0	99·3	99·7	99·6	102	98	3·0
Ba.M.	120·0	88·0	50	94·3	4173	1620	98·8	100·2	100·3	120	120	3·0
Ba.M.	120·2	87·9	100	94·1	3518	1396	98·8	99·4	100·0	105	110	3·0
Ba.M.	119·1	87·8	295	93·8	2880	408	98·8	99·6	99·8	110	102	4·0
Ba.M.	119·7	88·0	600	93·1	3318	298	98·8	99·7	99·5	106	104	4·0

TABLE 13A

Experiments of Dunham et al. The effects of different air speeds at dry-bulb temperatures 90°, 100° and 120° F and wet-bulb temperatures 83° and 88° F on men sitting throughout the four-hour experiments and wearing shorts

Subject	Environment				Sweat loss (g)		Rectal temperature (°F)			Pulse (beats/min)		Comfort Rating
	Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Effect. temp. (°F)	Total (4-hr)	In clothes	Initial	Average for last 3 hr	Final	Average for last 3 hr	Final	
Bg.Je.	92·3	83·1	10	85·7	515	77	99·1	98·3	98·5	88	78	4·5
Bg.Je.	89·8	83·9	100	83·5	415	10	98·7	98·3	98·6	76	76	3·5
Bg.Je.	90·0	83·0	290	81·0	252	0	98·5	98·2	98·2	80	78	4·5
Je.	90·0	83·0	520	78·6	305	10	99·0	98·0	98·4	89	84	4·0
U.C.	92·4	87·9	10	88·8	772	196	99·0	99·2	99·4	96	96	4·0
U.C.	90·2	88·0	100	86·8	625	77	98·7	98·9	98·9	83	80	4·0
U.C.	90·2	88·0	310	84·1	318	25	98·8	99·0	99·2	92	82	4·5
U.C.	90·2	87·9	520	82·1	263	52	99·2	98·6	98·9	90	88	4·0
Bg.Je.	100·1	83·1	20	87·8	962	51	99·0	98·9	98·8	85	84	4·5
Bg.Je.	99·5	83·1	100	86·2	1121	35	98·7	98·5	98·4	78	72	4·5
Bg.Je.	100·1	83·1	290	85·2	1058	4	99·1	98·8	98·8	83	77	4·5
Bg.Je.	99·9	83·0	520	84·0	1123	0	98·6	98·6	98·6	83	80	4·5
U.C.	99·9	88·1	20	91·0	1588	330	99·2	99·9	100·0	107	110	4·5
C.	100·1	88·0	100	89·6	1326	176	99·2	99·3	99·6	105	100	4·0
U.C.	100·1	88·1	310	88·4	1088	25	99·3	99·3	99·4	102	94	4·5
U.C.	100·4	88·2	520	87·9	1174	17	99·1	99·3	99·6	92	93	4·5
Bg.Je.	120·0	83·1	50	91·8	2200	223	98·6	98·9	99·2	82	86	4·5
Bg.Je.	120·0	82·8	100	90·9	2033	61	99·0	99·0	99·0	89	84	4·0
Bg.Je.	120·3	83·1	290	90·7	2601	32	99·0	99·0	99·0	95	90	4·5
Bg.Je.	119·7	83·1	520	90·0	3328	18	98·7	99·0	99·2	93	86	3·0
U.C.	119·9	88·1	50	94·2	2779	389	99·0	99·7	99·8	110	108	4·0
C.	119·9	88·0	100	94·0	2610	258	99·5	100·0	100·1	109	112	4·0
U.C.	119·1	87·8	310	93·2	2748	73	99·1	99·8	99·8	97	88	4·0
U.C.	119·7	88·0	520	93·0	3205	65	98·9	99·8	100·0	103	108	3·5

TABLE 14A

Experiments of Dunham et al. The effect of increasing the air speed on the severity of the environment (dry-bulb 120°F, wet-bulb 88°F) as indicated by the 'Basic' Effective Temperature Scale and by the sweat losses and rectal temperatures of men working in shorts

Air speed (ft./min)	Effective temperature (°F)	Sweat loss (g in 4 hr)	Final rectal temperature (°F)
50	94·1	4934	100·55
100	93·5	3958	100·15
330	93·2	4218	100·25
660	92·8	4718	100·45

TABLE 15A

Correlation between the P4SR Index and the observed sweat losses in the experiments of Dunham et al.

Clothing	Metabolic rate (kcal. m^{-2}.hr^{-1})	No. of experiments	Mean no. of subjects in each expt.	Correlation coefficient (r)	r/S.E.
Overalls	111	52	3·27	0·89	6·3
Shorts	111	79	3·84	0·95	8·4
Overalls	54	49	2·55	0·92	6·4
Shorts	54	55	2·67	0·95	7·0
All experiments	—	235	3·17*	0·97	14·8

* S.D. 2·36; Range 1–19

TABLE 16A

Correlation between the P4SR Index and the observed final rectal temperature in the experiments of Dunham et al.

Clothing	Metabolic rate (kcal. m^{-2}.hr^{-1})	No. of experiments	Correlation coefficient (r)	r/S.E.
Overalls	111	49*	0·74	5·1
Shorts	111	77*	0·79	6·9
Overalls	54	49	0·9	6·2
Shorts	54	55	0·77	5·7
All experiments	—	230	0·88	13·5

* Experiments in which more than 50 per cent of the subjects failed to finish have not been included
Mean initial rectal temperature of experimental groups, 98·93°F, S.D. 0·336°F

TABLE 17A

Experiments of McArdle et al. The effects on sweat loss and rectal temperature of increasing the mean radiant temperature above the air temperature

a = shorts working; b = shorts resting; c = overalls working; d = overalls resting

Expt.	No. of subjects	Work clothing	Dry-bulb (°F)	Wet-bulb (°F)	Air speed (ft./min)	Globe—therm. temp. (°F)	Mean radiant temp. (°F)	Corrected effective temp. (°F)	P4SR	Sweat loss (g)		Rectal temperature (°F)	
										Total (4-hr)	In clothes	Initial	Final
1	6	b	109·0	89·7	75	114·9	121·8	94·0	2·5	2236	388	99·6	99·7
2	6	b	114·5	88·5	75	113·8	112·9	93·3	2·0	2327	191	99·2	99·6
3	4	a	115·5	88·1	75	116·9	118·8	93·7	3·6	3886	488	99·5	100·3
4	7	a	117·0	88·0	75	116·2	115·0	93·5	3·35	3805	468	99·1	100·0
5	3	a	105·2	88·7	75	107·5	110·3	92·1	3·25	3387	516	99·0	100·1
6	3	a	107·8	88·2	75	(107·4	107·0)*	92·0	2·85	2997	419	99·6	100·0
7	8	d	108·4	88·6	75	113·4	119·3	93·3	2·75	3421	1361	99·55	99·8
8	8	d	113·4	88·9	75	(112·9	112·0)*	93·4	2·45	3160	1040	99·1	99·7
9	3	d	108·2	89·0	50	117·5	126·2	94·2	4·45	3810	1567	99·5	100·9
10	3	d	117·5	89·1	50	117·2	117·0	94·3	3·25	3578	1468	99·6	100·0
11	7	d	118·9	82·2	75	122·2	126·1	91·4	2·85	2652	429	99·3	99·6
12	7	d	123·0	82·0	75	121·8	120·3	91·2	2·75	2446	267	99·1	99·4
13	7	c	108·3	87·5	75	112·6	117·5	92·7	4·6	5715	2020	99·4	100·8
14	7	c	112·4	87·1	75	(111·8	111·0)*	92·2	3·9	4204	1203	99·3	100·2
15	6	c	119·5	83·0	75	123·0	127·0	92·0	4·4	4253	1006	99·5	100·1
16	6	c	122·9	82·7	75	(121·8	120·3)*	91·6	4·1	4048	692	99·2	99·9

* Estimated values

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